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A SYSTEM DESIGN REQUIREMENTS TOOL FOR  
SATELLITE COMMUNICATIONS THROUGH  
NUCLEAR-INDUCED SCINTILLATION

SUBMITTED TO:  
HQ BALLISTIC MISSILE OFFICE  
AIR FORCE SYSTEMS COMMAND  
HORTON AFB, CA 92409-8408

PREPARED UNDER:  
CONTRACT NO. FD4704-85-C-0147

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## SECTION 1

### INTRODUCTION AND SUMMARY

#### 1.1 INTRODUCTION

This document is the final report for Contract F04704-85-C-0147, A System Design Requirements Tool for Satellite Communications Through Nuclear-Induced Scintillation. It reports all the work done by Stanford Telecommunications, Inc. (STI) on this Phase I SBIR contract, broken down according to the task structure originally proposed:

- Task 1 - Data Gathering
- Task 2 - Discrepancy Resolution
- Task 3 - Simulator Design
- Task 4 - System Design Requirements

The report begins with a discussion of the original problem and a summary of STI's approach. Each task is discussed in one of four subsequent sections.

#### 1.2 BACKGROUND TO THE PROJECT

The proposal for this contract was written in response to the following solicitation, published in the FY 1985 Department of Defense Program Solicitation, Number 85.1, Small Business Innovation Research Program:

##### Nuclear Scintillation on RF Propagation

"DESCRIPTION: Conduct a study of determine the nuclear scintillation effects on satellite RF propagation to ground terminals in the 7-8 GHz and 20-40 GHz frequency band. The study should characterize the fade depth, fade rate, and fade duration aspects of scintillation and shall have, as a primary objective, the problem of resolving major differences between existing scintillation studies. This study will be based on Defense Nuclear Agency's (DNA) latest work/mathematical models for nuclear scintillation and shall develop system design requirements for scintillation for the RF frequency band specified herein."

A literal reading of the solicitation would lead one to a study in which the data gathering and discrepancy resolution activities become the prime focus. As explained below, after some thought STI came to view the customer's requirements in different light. Those first activities, while undeniably important, are only a first step towards what would ultimately be of best service to the designer/specifier of future systems. The key is in the last sentence, where "system design requirements" are sought. This intimates that the final purpose of the data developed in the study is the determination of requirements for communication systems operating in the designated frequency bands through scintillating channels. That being the case, it was felt that a cookbook-style report, as a final product, would be less useful than an automated tool that could allow the user to develop communication system designs and observe their properties.

STI thus interpreted the customer requirement ultimately to be the provision of an automated computer simulation tool that would enable a user to iteratively determine system design requirements for a given set of communication requirements. The proposal that was submitted and accepted strongly reflected this orientation.

It becomes important at the outset to establish the niche that this tool would fill in relation to the other computer-based assets that have already been brought to bear on the problem. Computer programs that evaluate quantities of interest relevant to communications through a nuclear environment are not new. Defense Nuclear Agency (DNA) has been accumulating elements of such a model for several years and has achieved a quite comprehensive tool for deriving physical parameters of the medium as a function of the nuclear event, which are then converted to communication-related parameters. Several contractors, most notably Mission Research Corporation, have contributed to the development of this model.

The full DNA model was never intended as a system design requirements tool and would undoubtedly be misapplied to that task. Issues of concern would include:

- Excessive Run Time - the DNA model performs highly detailed calculations in a non-realtime mode, the result being that excessive real time would elapse if the model were run over simulation time sufficient to accumulate significant statistics of error rate and other parameters;
- Lack of Flexibility - the DNA model, with its emphasis on the ionosphere physics, was not designed for a trial-and-error process of arriving at communications configurations suitable for a specific environment. Had this been the case, certain flexibility features related to changes in modulation methods, spread spectrum techniques, interleaver spans, etc., could have been built in;
- Single Link Restriction - The DNA model does not handle simulation of multiple links. If the scenario of interest is, for example, a two-hop case (e.g., ground-to-space-to-ground), the results of the first hop must be fed as input to a second run to complete the calculation. Furthermore, the nature of the signal processing at the intermediate nodes is not taken into account.

The invaluable role, for both the community-at-large and for this specific effort, of the DNA model and the collected analyses that accompany it is not to be underestimated. It has already been the basis for specification of nuclear-induced communication threat for future systems such MILSTAR; and it is the foundation for the work reported here. The approach of the DNA model, however, is one of providing answers as correct in detail as possible to point problems. The tool that might ideally be sought by an individual confronted with the problem of coming up with a system design concept for a communication system (that must survive the nuclear environment) would be one that permitted rapid evaluation of numerous system architecture candidates to a depth of analysis sufficient to preserve clear distinctions among those candidates. It is toward that end that the reported endeavor is dedicated.

### 1.3 OBJECTIVES

Under this contract, a study has been carried out to begin the development of a software-based tool that will be useful in the specification and/or design of satellite communications at SHF and EHF through nuclear-induced scintillation. The two prime objectives of the study are (1) to characterize the scintillation environment via mathematical models and parameter values, and (2) to develop preliminary system design requirements for satellite communications systems through a scintillation medium. Step 1 has been achieved by the collection of experimental and model data obtained in other studies and the organization of that data in such a way that discrepancies and inconsistencies can be resolved by analysis and elementary computation. Fulfilling the objectives of Step 1 has resulted in the construction of a model and data base which have independent utility and upon which a computer simulation tool can be designed. This tool would permit simulation of ground-to-satellite-to-ground communications through scintillation and would serve as the basis to finally achieve Step 2 above, the full determination of system design requirements for such systems.

During Phase I, the simulator has been completed through the preliminary design stage. The actual simulator was to have been developed under a Phase II award and used to complete the capability from which full communication system design requirements could be generated. During the period of performance of this contract, however, the number of STI employees grew beyond the 500 average number required to qualify as a small business under the SBIR program. Although STI is thus ineligible to submit a Phase II proposal, objectives for both phases are listed so that the scope of the project can be assessed in full. Based on our conviction that the Phase I objectives have been achieved, STI would be willing to submit a proposal for the equivalent of the Phase II activities should alternative funding sources be identified.

The combined Phase I/Phase II objectives are as follows:

- Gather sufficient data to characterize the nuclear scintillation channel and the performance of communication systems that use it;
- Perform an assessment of the gathered data to select the elements that will be part of the model data base, and in the process resolve (where possible) apparent discrepancies among the various sources; Identify issues not resolvable within the Phase I effort and set them apart for Phase II;
- Design the overall functional structure and content of a computer simulation tool that can be used to quantify system design requirements;
- Make a preliminary assessment of communication system design features vs. requirements that can be used as a basis for selecting system concepts to be investigated via the simulator;
- Complete the identification and resolution of model features, as well as adding those that could not be included in the preliminary design or that come to light after the Phase I effort;
- Prepare functional and performance specifications for the simulator software;
- Using existing software development methodology, complete the allocation of functions to CPCI's and design the algorithms for all code units;
- Code, test and debug the simulator; and
- Test the simulator against cases jointly developed by STI and BMO.

The Phase I objectives are discussed in greater detail below.

### 1.3.1 Phase I Objectives

There are four specific Phase I objectives, each of which makes a unique contribution to assessing the feasibility of the combined Phase I/Phase II approach. In turn, these four help quantify the extent to which:

- Appropriate characterization data of the scintillation medium is available;
- Discrepancies in those data can be identified and resolved;
- The simulation tool can be acquired within the scope of the post-Phase I time/money resources; and
- The consummate capability of the entire tool package can aid in the development of system design requirements for communications through nuclear scintillating media.

Each objective is identified and discussed below.

#### Objective 1: Scintillation Model Data Gathering

The objective here is to gather all data that will be needed to characterize the scintillation environment. This includes, but is not limited to:

- The DNA model
- Experimental data
  - Nuclear
  - Environmental
- Theoretical models
- Models/parameter values derived from experiment.

Data up to DoD SECRET is considered eligible for the overall study, although the data reported in Phase I is restricted to UNCLASSIFIED.

The data gathering effort is guided by the impetus to answer the following questions:

- What are the accessible sources of data?
- Are there areas in which no data of a given type are available?
- Are there areas in which multiple, conflicting data exist?
- Is there sufficient information available to structure the simulation effort?
- Is there sufficient information available to provide analysis for:
  - Simulator preliminary design
  - Initial design requirements analysis?
- Which of the data are relevant to simulator design?

Section 2 of this report details the data-gathering effort.

Objective 2: Resolution of Model Differences

This activity continues throughout the Phase I study. The basis of the resolution is primarily analytical, but some of the resolution -- a small but rather detailed portion -- requires simulation assets and hence has to be deferred to a follow-on effort, where the software package becomes operational. In any event, those model or data differences that can be resolved without the use of the simulator are resolved in Phase I to enable the modeling, simulator design and preliminary system design requirements to proceed.

Questions to be addressed include:

- Are discrepancies attributable to:
  - Measurement tolerance
  - Scenario differences
  - Analysis errors
  - Varying model assumptions
  - Quantity of data
  - Gaps in theory?
- Are discrepancies critical (i.e., is performance highly sensitive to the data values)?
  - Which discrepancies should be investigated in detail?
- Can the discrepancies be resolved; and if so, how:
  - Data reduction
  - Analysis
  - Rejection of some data
  - Consistency checks on derived results
  - Simulation (Phase II)?
- What should be the disposition of unresolved discrepancies?

The output of this effort is a preliminary recommendation of a scintillation model appropriate to the remainder of the work. This model will be viewed as a strawman to be iterated throughout the study. The issues addressed and resolved are discussed in Section 3 of this report.

Objective 3: Simulator Preliminary Design

This major component of the proposed work must answer many questions. The primary objectives are to:

- Understand and quantify the role that simulation can and should assume in getting to the end result.

- Identify the functions that the simulator should perform and the contribution of each function to the ultimate goals.
- Determine how well it should perform
  - Run time
  - Accuracy
  - Depth of user friendliness.
- Examine the feasibility of designing and building a simulator that meets or exceeds all performance criteria.
- Translate the foregoing objectives into quantitative statements about the code, mathematical models and computer assets.

Successful achievement of the above objectives will enable the contractor to make a specific Phase II (or equivalent) proposal for simulator development. Our preliminary design is found in Section 4 of this report.

Objective 4: Preliminary System Design Requirements

It was anticipated that at the start of contract there might be a set of problems previously identified by the customer for which some initial design requirements might be sought. This proved not to be the case, and as a result activity under this objective has been deferred to a follow-on phase. Although the development of system design requirements for scintillation systems is perhaps best accomplished by the simulation approach, it is not the case that any results in this area must await operational status of the simulator. Using modeling data gathered earlier and the general understanding of the behavior of communication links in the presence of time varying media, criteria for design to cope with the fading depth, rate and durations can be developed early in the follow-on. Typical parameters to be addressed might include, but not be limited to:

- Communication parameters
  - Achievable data rate (range of values)
  - Signal bandwidth
  - Choice of spread spectrum technique
  - Modulation
  - Encoding
  - Interleaving
  - Multiple access technique
  - Power control
  - Satellite signal processing
  - Multiple access user model
  - Jamming model
- End-to-end performance requirements
  - Error rates (bit symbol, word, message, etc.)
  - Tolerable data delay
  - Synchronization (time, frequency, crypto)
- Operational features
  - Control strategies
  - Adaption procedures under scintillation onset or transient conditions.

The thrust of effort related to this objective has been in the identification of issues to be addressed and resolved in the follow-on. Section 5 of this report discusses that effort in detail.

#### 1.3.2 Commentary

An outcome of the work required to achieve these objectives is the identification of follow-on objectives. This is no more than an accurate accounting of the Phase I accomplishments ranked against the overall project objectives. The items so listed in Section 1.3 were derived in just that way.

It is STI's belief that the four objectives have been satisfied as completely as possible as a result of the Phase I effort. We have gathered a useful data base for the modeling effort, although there remain gaps; certain key discrepancies in the gathered data have been resolved, paving the way for a fairly complete model specification; a preliminary design of the simulator has been completed; and an understanding of basic requirements and issues to be resolved in a future effort has been accomplished. Achievement of the Phase II objectives under a follow-on award would now be possible.

#### 1.4 SUMMARY OF PHASE I

As stated before, the four Phase I objectives set forth in Section 1.3.1 have been adequately satisfied. The result of this work is a preliminary design of a simulator MASCOT (Model to Analyze Scintillation of Transmissions) for satellite communications through nuclear-induced scintillation. Specifically, the simulator would allow a user to (iteratively) determine system requirements based on the constraints of communications performance of alternative system realizations.

The simulator possesses several prominent features that make it a versatile tool for system analysis. First and perhaps most important, the simulator attempts to minimize the run time by utilizing available analytic results, whenever possible, minimizing computing requirements. Full-scale Monte Carlo simulations will be used only as a last resort when analytic approaches are inadequate.

Second, independent of whether the simulation or analytic approach is used to obtain system requirements, the simulator offers functional versatility. That is, it incorporates the possibility of channel environments characterized by several different fade statistics, including Rayleigh. Also, the simulator takes into consideration numerous system component features, namely different modulation, interleaving, coding, receiver/equalization, among others. Finally, the simulator has the capability to assess multiple link systems

(with and without intermediate onboard satellite processing), as well as the standard single link system. It should be noted that links with different scintillation modes/layers within that link can be analyzed also, accounting for a multiple-striation fade environment.

With these features set forth in Phase I, it is apparent that the simulator is a flexible tool, capable of assessing many communications systems and environments. Continuation into a follow-on contract would satisfy the ultimate goal of realizing and implementing the simulator.

The simulator is defined by flow charts depicting the activities of each of its major components, identification of a hierarchy of simulation modules to execute the various functions, and functional descriptions of each module. The functional descriptions are specified at the level of mathematical equations for signal processing or logical descriptions of the decision processes being modeled. How these modules are interconnected is shown by the hierarchy charts. Flow charts indicate the sequence of actions, something not readily discernible from the interconnections or module descriptions alone.

The resulting model description is viewed as a preliminary design. In the process of building the simulator, it will change many times. What has been accomplished that is important is that the process of coming to a preliminary design has been worked out by a complete pass through the design. Further iterations to be accomplished in a follow-on effort will fit the pattern of this development.

## SECTION 2

## DATA GATHERING AND MODEL FEATURES

This section describes the data gathering effort and the resulting reduction of the data into a model from which the requirements analysis tool, called Model to Analyze Scintillation of Transmissions (MASCOT), can be generated. A summary of the model and proposed simulator features is also presented.

## 2.1 DATA GATHERING EFFORT

STI has assembled more than 30 documents relating to communications via nuclear-disturbed channels. Sources for these included:

- Open literature
- Government-funded study reports
- Government system specifications or requirements documents
- Documentation of the DNA simulation model.

A comprehensive bibliography is presented within the report. Among the sources gathered are those authored by MRC, SRI, GE, ESL and DNA.

The bulk of the literature surveyed was unclassified (only the Government system reports and a few studies carried DoD classifications). Based on studying the mix of classified/unclassified facts, the following conclusions were reached:

- The essence of the model attributes and parameters can be conveyed using unclassified data; therefore, this report is entirely unclassified.
- The full simulation model will, however, have to incorporate classified data, and will therefore have to be approached as a classified software project.

The collected literature discusses most of the significant facts about the nuclear channel. Key areas included are:

- Physical models for the transmission medium
- Characteristic parameters of the channel
- Analytic results for communications performance under a variety of signaling strategies
- Time and frequency domain simulation techniques.

Data from all these areas have been incorporated into the model upon which the simulator is based. The following section summarizes the most important features attributable to the nuclear channel.

## 2.2 NUCLEAR DISTURBED CHANNEL CHARACTERISTICS

The communications model proposed by STI for the scintillation channel was developed following examination of a variety of other models. It is intended to provide the user with a capability to examine communications in the nuclear scintillation environment that is: (1) comprehensive in terms of the range of scintillation effects and communications functions that may be modeled; (2) accurate to within known limits; (3) flexible to modification; and (4) practical to use. Below we review key features of the nuclear channel. The section that follows will discuss the summary features of the model developed by STI.

The data gathering effort had a goal of finding a means of parametrically characterizing the nuclear scintillation channel and identifying the communications functions and parameters necessary to implement in developing a modeling tool with broad applicability. Almost all of the models observed characterized the scintillation channel in parametric terms because of the difficulty of actually modeling the complex interactions between the

ionosphere and the transmitted signal. Key parameters such as decorrelation time ( $\tau_0$ ), electron density fluctuation ( $\sigma_n$ ), phase variance ( $\sigma$ ) and others to be discussed in detail in later sections recur as the basic characteristics that affect communications through the channel.

A high altitude burst (HAB) markedly disturbs the free electron structure of the ionosphere from its nominal state. This disturbance can occur over geographic regions the size of several states. Total electron count is greatly increased by the ionizing properties of the burst, and the resulting electron density exhibits large-scale spatial irregularities and time variations.

It is the electron density that most influences the characteristics of RF transionospheric propagation. Models developed by DNA and its contractors indicate rod or sheet-like layers of electron concentration that manifest themselves in various ways in a signal that traverses them.

Small random changes in the refractive index will perturb the phase velocity and resultant phase-front characteristics of the incident signal. Larger disturbances effect the propagation or group velocity as well, introducing random delay dispersion across the wave. These effects can combine to cause contour tilts that displace the local direction of propagation and induce apparent wander into the arrival angle of the signal. Wide angle scattering and absorption will attenuate the direct path component. Diffractive combining of these signals produces amplitude variations, called fading or scintillation. Thermal noise emitted by "hot spots" will raise the link noise temperatures.

The extent to which each of these effects occurs depends upon the signal frequency, and hence its frequency spectrum. For a wideband waveform, uncorrelated effects occurring at separated frequency regions may appreciably distort the waveform. Scintillation, in particular, can exhibit frequency dependence. Within a bandwidth denoted as the coherence bandwidth, the fading amplitude is roughly constant, but outside that bandwidth it becomes independent of the fade value within the bandwidth.

The medium will exhibit short and long term temporal variations. The short term variations arise in small scale motions of density regions, and these show up as doppler shifts. The longer term properties result from the settling out the HAB-induced transient. Immediately following the burst, the environment is most chaotic and variable (prompt effects). Coherence times and bandwidths take on their smallest values. With time, the transient spatial properties of the medium become more nearly uniform, and eventually the long term time variation rates decrease and stabilize. In the long term the medium is usually well modeled as a Raleigh channel.

Parameter values associated with the scintillation model vary with frequency. Absorption, for example, varies as  $1/f^2$ , which means that in a satellite system, downlink outage (the lower frequency) may be more frequent or of greater duration than the uplink outage. The push to higher frequencies (EHF) is supported by this finding.

## 2.3 MODEL FEATURES

### 2.3.1 Fast vs. Slow Fading

When viewed from a communication perspective, the scintillation channel may be described as exhibiting either fast or slow signal fading conditions. Further, scintillation events may be described as frequency-selective or nonselective (flat) dependent upon their effect on carriers transmitted at different frequencies. The precise characteristics and severity of the nuclear scintillation environment was found to be dependent upon size of the nuclear detonation, location of blast relative to the transmitter/receiver pair, and time after blast.

The decorrelation time (time between "independent" fading samples) is probably the most significant parameter in terms of describing the severity of ionosphere disturbances. The ratio  $\tau_0/T$  (decorrelation time divided by the channel symbol duration  $T$ ), referred to as the normalized decorrelation time, is frequently utilized as the means of describing the rapidity of fades. Large values of  $\tau_0/T$  ( $\tau_0/T > 1$ ) are described by saying that slow fading

conditions prevail, while small values of  $\tau_0/T$  are indicative of fast fading. To understand this, note that small values of  $\tau_0/T$  indicate more frequent occurrences of independent scintillation events relative to the symbol duration, and therefore a faster fade environment is expected.

It was found that, in general, the slow fading regime better succumbs to analytic modeling. Error probability formulas can be devised to represent expected performance under varied communication scenarios. These formulas require as input only the receiver signal-to-noise ratios and the identification of the signaling strategy (mod/demod, code/decode, spread/despread, etc.). The fast fade case, however, is more likely to require simulation techniques to represent the received waveforms and the processing performed on them. There is naturally a concern that excessive run times could result in processing the amount of data required to generate sufficient accuracy. For completeness, a fast fade simulator approach to cover those cases is presented in this document. The suggested manner of its use, however, requires some discussion.

One choice is to implement the fast fade module as described in this report (Section 4.4) as the production version. Two other choices are possible, however: (1) create an interface in the STI model through which an external simulation of fast fading may be attached (e.g., the DNA model); or (2) implement the fast fade module as given, and then via thorough test and experiment, find analytic or tabular representations of its output that then replace it as the production version. These two alternatives are presented as means to alleviate the possibility that the run times associated with the fast fade simulator dominate the usage and subvert the original goal of having a "quick result" type of tool. Adjudication of the preferred strategy will await a Phase II effort.

### 2.3.2 Multi-Link Capability

Previous models of the scintillation channel have concentrated on single link propagation. The signals originating at, for example, an earth terminal pass through the scintillation medium and impinge on the receive antenna, say, in

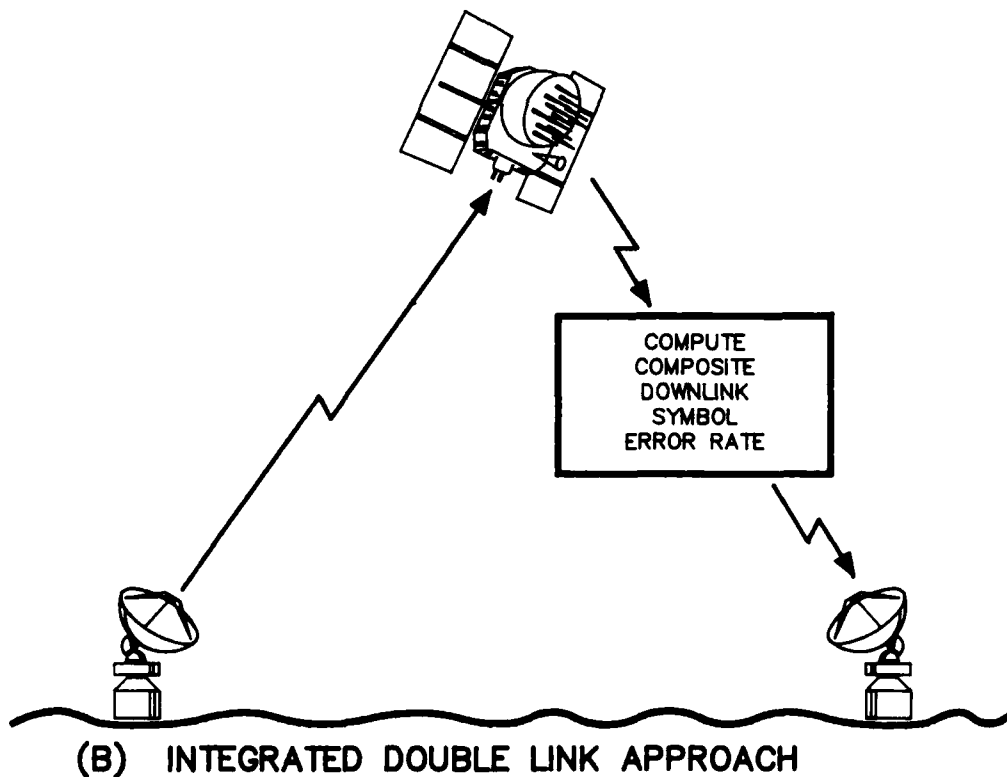
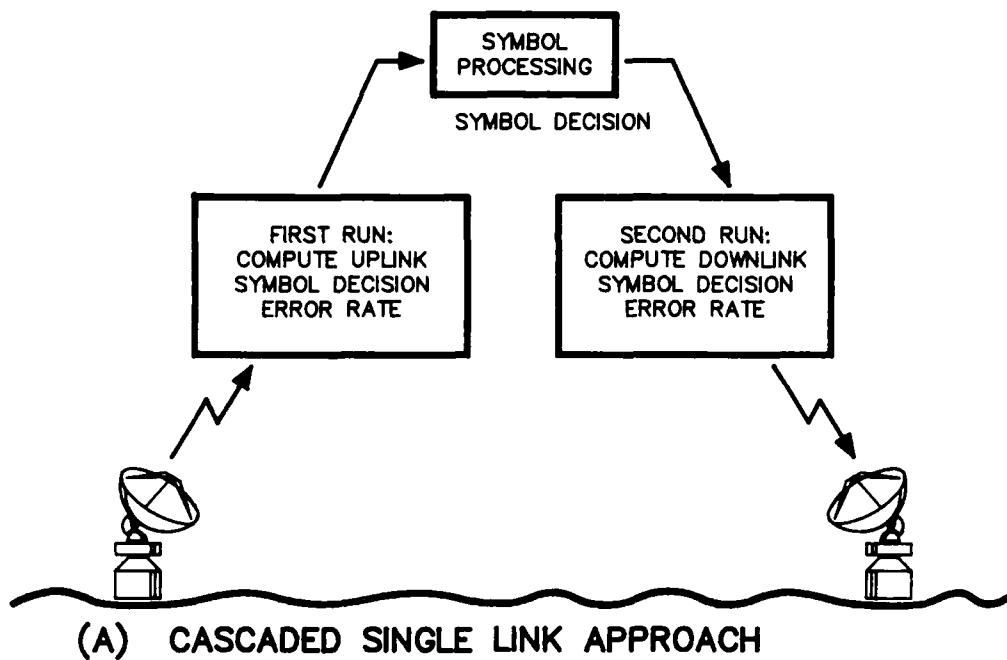
space, following which signal processing for data detection occurs. If there is a second link -- space-to-ground, for example -- it would have to be modeled by a similar sequence of events.

This procedure has some drawbacks. As illustrated in Figure 2-1(a), it requires two simulation runs, with some intermediate processing in which the output data from the first run is reprocessed to format it as input to the second. An implicit consequence is that the output data from the first run must be digital symbol decisions, anywhere from demodulated channel symbols down to the decoded bit stream. If the transponder is a repeater and does not process inputs down to this level, then the two-link simulation technique cannot give a faithful reproduction of system to be modeled.

The design of MASCOT has taken some steps to avoid these pitfalls. Figure 2-1(b) illustrates the built-in facilities for this purpose. If data passes through the scintillation environment twice, the analyses have been carried out to model the end-to-end channel, bypassing the intermediate results at the transponder. Depending on the geographical location of the terminals, the two passes through scintillation could be modeled as independent samples of either the same or two different fading media, as shown in Figure 2-1(b). This feature is one designed to achieve the improvements in run speed claimed for MASCOT.

### 2.3.3 Communication Orientation

The initial steps taken by the community-at-large interested in scintillation modeling were necessarily aimed at understanding the physics of the trans-ionospheric propagation. With time a clearer picture of this has emerged to the point where many of the salient features yield to analytic modeling. This development allows the system engineer to put the focus of his effort in the proper spot -- communications. MASCOT is a communications-oriented tool. In considering the design tradeoffs for it, STI has intentionally opted for simplicity of modeling versus absolute accuracy of results. The utility of MASCOT is lost if it becomes another number-crunching detailed simulator. To achieve this end naturally requires incorporating the best of available



10/13-TR880138\p08011

FIGURE 2-1: TWO APPROACHES TO CASCADE LINK PERFORMANCE ANALYSIS

analyses or providing our own where necessary, and being open to continued revision of approaches during the early phases of a follow-on software procurement award. A key part of such a follow-on would be to perform error analyses for the algorithms implemented so that a quantified understanding of accuracy would be available. But the intent will always be to emphasize communications in the models so that the user can study communications alternatives, not scintillation physics.

The extent to which this is the case for MASCOT will be seen in Section 2.4, where a detailed list of functions modeled is given. The scintillation channel model is in all cases reduced to the parameters that are most crucial to the behavior of the communications signaling. It is STI's intent to maintain this spirit in the evolution of MASCOT.

#### 2.3.4 User Friendly Features

The user-friendliness qualities of MASCOT, in general, enhance the interaction between the user and MASCOT. These features are characterized by giving the user guidance and prompts at every step as required. The chances of setting up and executing runs with erroneous data inputs are thereby considerably reduced. At the parameter initialization, which will prepare MASCOT for link performance evaluation, the user is given tentative bounds (where appropriate) for each parameter; parameter values out of this range would most likely result in unrealistic or highly sub-optimal communications systems.

Following initialization, any parameter not assigned a value by the user will be given one automatically by default from MASCOT's permanent database. These default values will be "typical" of actual communications systems parameters in existence.

MASCOT also performs error checking on the user-inputted data. Error checking entails both syntactical and functional data verification. Parameters with blatant syntax errors are rejected by MASCOT, and the user is required to input new values for those erroneously assigned parameters. Furthermore, MASCOT checks for functional errors, making sure that the "out-of-bound errors" are not mistakes, but rather intentionally unorthodox system parameter sets.

After accepting the required changes necessitated by the error check, MASCOT allows for user data revision. This revision ensures that the system being investigated is, in fact, the one specified by the user. Therefore, any of the system parameter values (such as those he may have overlooked initially), may be changed as often as necessary or desired. The new values will be inspected by MASCOT for errors, as done previously.

Following a link performance evaluation, MASCOT displays analysis/simulation results in an unstructured format. The user then is allowed to view the same result data in one or more organized forms selected by the user: tables, graphs, or plots. Hence, because of the visual enhancement, link performances using different parameter sets can be compared and contrasted more effectively.

After MASCOT has displayed link evaluation results, the result data are stored in a permanent external database file; the data are also stored in MASCOT's execution database for subsequent link evaluations, if the user wishes. Otherwise, the results are stored only in the external database, and the portion of the execution database containing data for the current link is cleared. The current link is reinitialized by the user, and the performance of the link is evaluated again for the new parameter values. This process can repeat indefinitely, until the user is satisfied.

Finally, MASCOT automatically updates the previous link results stored in the execution database for next-link performance evaluations (if there are more links in the system). Those updated parameters are displayed again to the user for verification and revision, and MASCOT's execution cycle repeats.

#### 2.3.5 Generality

MASCOT is also a general tool, applicable to a variety of communications system specifications. In addition, different channel conditions can be taken into consideration. MASCOT can incorporate several forms of diversity options into the communications system under study. These options include time diversity (coding, interleaving), frequency diversity (multi-tone, spread spectrum, etc.), and spatial diversity. The user can choose various combinations of the above diversity methods for link performance improvement.

Several different modulation schemes are also made available to the user by MASCOT for system performance study. They include phase shift keying, frequency shift keying (coherent and noncoherent), and differential phase shift keying. Multiple signaling alphabet options are also given to the user.

In addition to the different modulation types, the user is permitted several receiver (or receiver algorithm) options. Each receiver has its own particular advantage in system performance, which the user may investigate with repeated runs for the same link using the user-friendly revision option.

Finally, using the parameters entered at initialization, MASCOT automatically calculates the various channel modes for the communications links. These modes include fast Rayleigh fades, slow Rayleigh fades, Rician fades, etc. Since appropriate computational components are enabled to determine link performances, the user does not have to perform any calculations prior to executing MASCOT.

#### 2.4 MODEL SUMMARY

The key functions modeled and the relevant parameters are summarized in Table 2-1. These functions span the transmit parameters, the channel parameters and the receive parameters. The details of these functions will be seen in Section 4 where the software design is given.

**TABLE 2-1**  
**KEY FUNCTIONS TO BE MODELED**

FEATURE	KEY PARAMETERS PERTAINING TO EACH FUNCTION	
	INPUTS	OUTPUTS
<b>TRANSMITTER</b>		
<ul style="list-style-type: none"> <li>• INFORMATION</li> <li>• CODING               <ul style="list-style-type: none"> <li>- CONVOLUTIONAL</li> <li>- BLOCK</li> </ul> </li> <li>• INTERLEAVING               <ul style="list-style-type: none"> <li>- CONVOLUTIONAL (SYNCHRONOUS)</li> <li>- BLOCK</li> </ul> </li> <li>• DIVERSITY               <ul style="list-style-type: none"> <li>- FREQUENCY</li> <li>- SPATIAL</li> <li>- TIME</li> </ul> </li> <li>• SPREAD SPECTRUM               <ul style="list-style-type: none"> <li>- FREQUENCY HOPPING</li> <li>- PSEUDO-NOISE</li> <li>- HYBRID</li> </ul> </li> <li>• MODULATION               <ul style="list-style-type: none"> <li>- BPSK (COHERENT)</li> <li>- QPSK (COHERENT)</li> <li>- DEBPSK (COHERENT)</li> <li>- DPSK (COHERENT/ NONCOHERENT)</li> <li>- BFSK (NONCOHERENT)</li> <li>- M-FSK (NONCOHERENT)</li> </ul> </li> </ul>	ALPHABET  $\hat{m}(t)$ , $r$ , $K$ $\hat{m}(t)$ , $a$ , $K$  $a_2, a_1, D, S, I_L, \tau_o$ $I_r, I_c$  $N$ $L$ TBD  $W, PG, R, \text{HOP RATE}, f_c, \tau_o, L$ $W, PG, R, \text{CHIP RATE } \tau_o$  $E_b/N_o, R, T_s, B_L, f_c$ $E_b/N_o, R, T_s, B_L, f_c$ $E_b/N_o, R, T_s, B_L, f_c$ $E_b/N_o, R, T_s, f_c$  $E_b/N_o, R, T_s, f_\Delta, f_c$ $E_b/N_o, R, T_s, f_\Delta, f_c$	MESSAGES OUT $\hat{m}(t)$  CODE WORDS OUT CODE WORDS OUT  INTERLEAVED SEQUENCE  INTERLEAVED SEQUENCE  FREQUENCY DIVERSIFIED SIGNAL SPATIALLY DIVERSIFIED SIGNAL TBD  FREQUENCY SPREAD SIGNAL FREQUENCY SPREAD SIGNAL  TRANSMITTED SPREAD $S(t)$ - - - - - -
<b>PROPAGATION</b>		
<ul style="list-style-type: none"> <li>- GENERAL</li> <li>- AWGN CHANNEL</li> <li>- SCINTILLATION CHANNEL               <ul style="list-style-type: none"> <li>-- SLOW FADING</li> <li>-- FAST FADING</li> <li>-- FREQUENCY SELECTIVE</li> </ul> </li> </ul>	$S(t), f_c, T_x/R_x \text{ LOCATIONS}$ $N_o = K T_{\text{atmosphere}}$ $\tau_o, \sigma_a, \Phi, E(t, r), h(t, \epsilon)$ $V, \text{TIME AFTER BLAST}$ $\tau_o/T, \text{BPSK, DEBPSK, DPSK}$  $\tau_o/T, \text{BFSK, MFSK}$  $\tau_o/T, f_o, \text{BPSK}$	$r(t) \triangleq \text{GAUSSIAN R.V.}$ PHASE & AMPLITUDE SCINTILLATIONS $r(t) = \text{FADED SIGNAL}$
<b>RECEIVER</b>		
<ul style="list-style-type: none"> <li>• DEMODULATION &amp; TRACKING               <ul style="list-style-type: none"> <li>- COHERENT                   <ul style="list-style-type: none"> <li>-- CARRIER PHASE TRACKING LOOP</li> <li>-- COSTAS LOOP</li> <li>-- SQUARING LOOP</li> </ul> </li> <li>- SYMBOL DELAY TRACKING LOOP</li> <li>- AGC LOOP</li> <li>- WAVEFORM'S                   <ul style="list-style-type: none"> <li>-- BPSK/DEBPSK</li> <li>-- QPSK</li> <li>-- OPSK</li> </ul> </li> </ul> </li> </ul>	$r(t) = [(t)+i]q(t)$ $\phi, BW_s, f_c, t_s, T_{\text{effective}}$  $B_L, \text{ORDER}, \tau, I_k, Q_k, \hat{m}$ - $t_1, I_k, Q_k$ $I_k, Q_k$  $E_b/N_o, R, T_s, B_L, \tau_o$ - -	IF $f_o T \geq 1.0$ THEN DEMOD OK $I_k, Q_k, f_o T \geq 1$  $e_c$ - $e_d$ $e_a$  IF $\tau_o B_L \geq 4 \rightarrow \text{RAYLEIGH LIMIT}$ IF $\tau_o B_L \geq 12 \rightarrow \text{RAYLEIGH LIMIT}$ IF $\tau_o B_L \geq 8 \rightarrow \text{RAYLEIGH LIMIT}$

**TABLE 2-1**  
**KEY FUNCTIONS TO BE MODELED (Cont'd)**

FEATURE	KEY PARAMETERS PERTAINING TO EACH FUNCTION	
	INPUTS	OUTPUTS
<ul style="list-style-type: none"> <li>• NON-COHERENT DEMODULATION               <ul style="list-style-type: none"> <li>AUTOMATIC TRACKING LOOP</li> <li>SYMBOL TRACKING LOOP</li> <li>AGC LOOP</li> <li>WAVEFORMS                   <ul style="list-style-type: none"> <li>BFSK</li> <li>MFSK</li> <li>DPSK</li> </ul> </li> </ul> </li> <li>• EQUALIZATION               <ul style="list-style-type: none"> <li>ADAPTIVE</li> <li>NON-ADAPTIVE</li> </ul> </li> <li>• DESREADING               <ul style="list-style-type: none"> <li>FREQUENCY HOPPING (FH)</li> <li>PSEUDO-NOISE (PN)</li> <li>HYBRID COMBINATIONS</li> </ul> </li> <li>• CHIP COMBINING               <ul style="list-style-type: none"> <li>FREQUENCY DIVERSITY</li> <li>SPATIAL DIVERSITY</li> <li>TIME DIVERSITY</li> </ul> </li> <li>• DEINTERLEAVING               <ul style="list-style-type: none"> <li>SYNCHRONOUS (CONVOLUTIONAL)</li> <li>BLOCK</li> </ul> </li> <li>• DECODING               <ul style="list-style-type: none"> <li>CONVOLUTIONAL</li> <li>BLOCK</li> </ul> </li> </ul>	$I_k, Q_k$ $I_k, Q_k$ $I_k, Q_k$ $E_b/N_0, R, T_s, \tau_0$ $\Delta f$ $\Delta f$ $\dots$ $I_k, Q_k$ $C.(k), E_k, \hat{M}_k, \delta, a, \text{OVER-HEAD DUE TO TRAINING SEQUENCE}$ TBD $W, PG, \tau_0$ HOP RATE, N CHIP RATE TBD  N, SPREAD BW L REFER TO CODING AND INTERLEAVING  $a_1, a_2, D_a, S_a, I_L, \tau_0$ TBD  $R_c, K$ $a, K$	$e_f$ $e_d$ $e_a$ $\tau_0 \Delta f \geq 3$ $\tau_0 / T \geq 8$ $I_{kEQ}, Q_{kEQ}, q_{k+1}$  TBD DESPREAD SIGNAL   TBD TBD  DEINTERLEAVED SEQUENCE (RANDOMIZED ERRORS)  DECODED SYMBOLS

## SECTION 3

## RESOLUTION OF MODEL DIFFERENCES

In the process of developing the STI model, a number of significant issues arose. Typically, these issues focus upon choices of key model functions and I/O parameters, as well as conflicts between the STI model and others examined. These and other issues will be treated in the paragraphs that follow.

## 3.1 MODELING APPROACH

The first class of differences to be examined are those pertaining to model approach. One of the significant differences noted between studies and models observed was the degree to which emphasis was placed on simulation as opposed to analytical techniques. Most of the models observed were simulation based. This is probably because no general analytical solution exists for determining communications link performance in the nuclear scintillation environment. However, models such as presented in the DNA paper entitled "Binary Error Rates for Two-Component Scintillation Channel" [20] were essentially analytical, and could be solved numerically for special cases in which the channel conditions reduce to known forms, for example, a Rayleigh density under slow fading conditions. When more general conditions are considered, simulation is necessary as numerical solutions become increasingly complex. The MPS and PATS propagation models [2, 3, 7, 11] are essentially simulation based. That is to say that regardless of whether the scintillation conditions could be denoted as fast, slow or frequency selective, the results were obtained essentially through simulation.

For the purposes of the STI nuclear scintillation modeling tool, analytical/numerical techniques will be used to advantage. Specifically, their use appears appropriate in the slow fading region where the channel can be approximated by Rayleigh Fading and other known distributions and inherent time savings over simulation realization. Fast fading conditions would still require simulation. As a result, the STI model will be a hybrid that combines both analytical/numerical techniques with Monte Carlo simulation enabling the user

to determine the SATCOM system performance under a wide range of conditions. The model would provide the user with an array of standard communications functions with which to study communications through a nuclear scintillation environment, as well as the capability to implement new functions due to its modularity.

### 3.2 FADING TIME FIGURE OF MERIT

Differences were also observed regarding figures of merit. For example, the ratio  $\tau_0/T_s$  was frequently used in output plots. As already noted, it was found to be an effective way to delineate fast from slow fading conditions. Variations of  $\tau_0/T_s$  were also observed. For example, the coded symbol duration ( $\tau_c$ ) was sometimes used in place of the channel symbol duration ( $T_s$ ). Additionally, use of the inverse ratio ( $T_s/\tau_0$ ) was also observed and referred to as the relative fading bandwidth. These differences were not considered major; however, they are worth noting because they are evidence of the significance most studies placed upon this ratio.

Models also differed in terms of their approach to handling the fast and slow fading environments. Some references defined specific ranges of  $\tau_0$  as indicative of fast or slow fading. The decorrelation time may be interpreted as the duration of an independent scintillation event, and several studies refer to fast fading as being related to, even synonymous with, small values of  $\tau_0$ . However, performance appears to be more effectively determined by  $\tau_0/T_s$ , and this ratio appears more appropriate than  $\tau_0$  alone as a measure of the fading effects induced by scintillations. This would appear to be true because for  $\tau_0$  several times greater than  $T_s$  then it is expected that many transmitted symbols would be expected to pass before occurrence of a scintillation event, and a potential fade. On the other hand, if  $\tau_0$  is smaller than  $T_s$ , then it seems likely that one or more independent scintillation events would be expected during any given symbol period. Therefore, the following is considered: (1) that  $\tau_0$  is considered as one of the key parameters in describing the severity of the scintillations (rate); and (2) that the ratio  $\tau_0/T_s$  (or a similar ratio) more accurately describes the effects of a given scintillation

channel characterized by decorrelation time,  $\tau_0$ , on a communications system with an established data rate and modulation technique. Nevertheless, an issue still remains to be resolved in precisely discriminating between slow and fast fading conditions.

### 3.3 OTHER CHANNEL PARAMETER DEFINITIONS

While  $\tau_0$ , also referred to as the coherence time  $(\Delta t)_C$ , was readily identified as a key, others were not as easily identified. Specifically, channel parameters such as the frequency selective bandwidth  $(\Delta f)_C$ , the spectral bandwidth  $(B_{sp})$ , and the coherence bandwidth  $(B_C)$  were noted from various references and required clarification.

The frequency selective bandwidth and the channel coherence bandwidth were both found to be defined by:

$$B_C = (2\pi\sigma_t)^{-1} = (\Delta f)_C$$

when  $\sigma_t$  is the standard deviation of the signal time-delay jitter. Therefore, these parameters were identified as equivalent. It is worth noting that the above relationship is sometimes stated thus: the channel coherence bandwidth is defined to be roughly inversely proportional to the multipath spread:

$$(\Delta f)_C \approx \frac{1}{T_m}$$

Here  $T_m$  is essentially the time duration of the essentially nonzero portion of the channel delay power spectrum, the significance being that if  $(\Delta f)_C$  is small compared to the instantaneous bandwidth of the transmitted signal, then the channel is referred to as frequency-selective. Frequency-selective channels may result in severe signal distortions. By contrast, large values of  $(\Delta f)_C$  compared to the bandwidth of the transmitted signal result in frequency-nonselective, or flat fading. As a result, a reference to frequency-selective bandwidth implies that the channel coherence bandwidth is in fact small compared to the transmitted signal bandwidth and that the channel is frequency-selective.

The spectral bandwidth was defined as proportional to the inverse of the decorrelation time:

$$B_{sp} = \frac{.225}{\tau_0}$$

Therefore,  $B_{sp}$  was found to be related to the Doppler spread of the channel ( $B_d$ ), which was observed to be similarly defined:

$$(\Delta t)_c \approx \frac{1}{B_d} \approx \tau_0$$

Finally, it is noted that a slowly changing channel would be one with a large decorrelation time. Larger values of  $\tau_0$ , as noted previously, correspond to less severely disturbed scintillation channels. Therefore, it is clear that large values of  $\tau_0$  imply only a small Doppler spread, while small values imply larger Doppler spread and more severely distorted channel.

Other figures of merit were observed such as the signal-to-channel scintillation noise ratio (SCR) defined as follows:

$$SCR = \frac{V^2/2}{\sigma_c^2}$$

where  $\sigma_c^2$  was defined to be the scintillation noise power, and  $V^2/2$  was the signal power. Because of its modularity, the STI model will enable the user to define figures of merit as desired for output graphs, as well as providing a basic set of output carries such as BER vs.  $\tau_0/T_s$ .

### 3.4 SCENARIO PARAMETERS

There were a number of scenario-related issues that also had to be resolved, and to some extent, remain to be resolved. First, it was necessary to isolate the differences between the scintillation environment under "normal" conditions from those under nuclear-induced stress. Generally speaking, the range of decorrelation times observed at any frequency is broader under nuclear-induced conditions. This is especially true of the low end (i.e., very small

values of  $\tau_0$ ). Further, frequency selective fading is much more likely under the severe conditions imposed by a high altitude nuclear burst. Both fast fading and frequency-selective fading are therefore more likely to occur. In each case, these conditions are likely to be found shortly after a detonation and to diminish with time, although as under normal conditions, the severity and extent of scintillation effects is strongly dependent upon carrier frequency. Finally, it is noted that many studies do not specifically identify such parameters as time after burst, blast size and location relative to a communications link as key parameters. However, they are key because of their direct relationship to severity of the scintillation environment and to the user's comprehension of the cause-and-effect relationship between threat, and communication system performance. While it remains to be determined as to how these and other scenario-related concerns (e.g., EMP's, dust, etc.) enter the model, it is intended that they be available for the purposes of output plots because they are considered to enhance the utility of the model.

### 3.5 COMMUNICATIONS STRUCTURES

A variety of receiver structures were observed from the literature. In the MRC study of frequency selective receivers by Bogusch [3], both noncoherent and coherent receivers were based upon the same modular structure. The main difference is in the use of an automatic frequency control loop (AFC) instead of a modified Costas loop. It is significant to note that both noncoherent and coherent receivers could be implemented from the base receiver structure. Most of the other models considered generic receivers, and while similar in concept they were not necessarily modular. For example, the MRC study previously mentioned contained separate and distinct receiver structures for each modulation technique. While the end result is essentially the same, it appears more practical for the purposes of this model to modify a single generalized receiver for coherent or noncoherent reception rather than to implement a new structure each time a different modulation technique is considered.

## SECTION 4

## SIMULATOR PRELIMINARY DESIGN

## 4.1 GUIDE TO THE SYSTEM DESCRIPTION

4.1.1 General

The solicitation published in the FY 1985 Department of Defense Program Solicitation, Number 85.1, Small Business Innovation Research Program, entitled "Nuclear Scintillation on RF Propagation", requests that a study be conducted to determine the nuclear scintillation effects on satellite RF propagation to ground terminals in the 7-8 GHz and 20-40 GHz frequency bands, and to develop system design requirements for scintillation for these RF frequency bands. The problem of developing design requirements for communications systems that must meet a given set of communications requirements while operating through scintillation-affected channels is one that remains to be solved conclusively, despite many recent advances.

STI communications engineers, upon carefully analyzing the ramifications of the problems outlined in the solicitation, concurred that computer simulation, carefully tailored to the problem would be the innovative and optimal approach to developing system design requirements for communication systems within the classes detailed in the solicitation. The computer simulation methodology developed under contract provided the inputs for the preliminary design of MASCOT, the Model to Analyze Scintillation Of Transmissions.

MASCOT is envisioned as an automated computer simulation tool that will aid the communication analyst in the development of system design requirements for communication systems, including ground-to-satellite-to-ground systems, operating within accepted frequency bands through nuclear scintillating media. MASCOT would permit the analyst to define the scintillation-affected environment in which the communication system would operate, and then rapidly execute

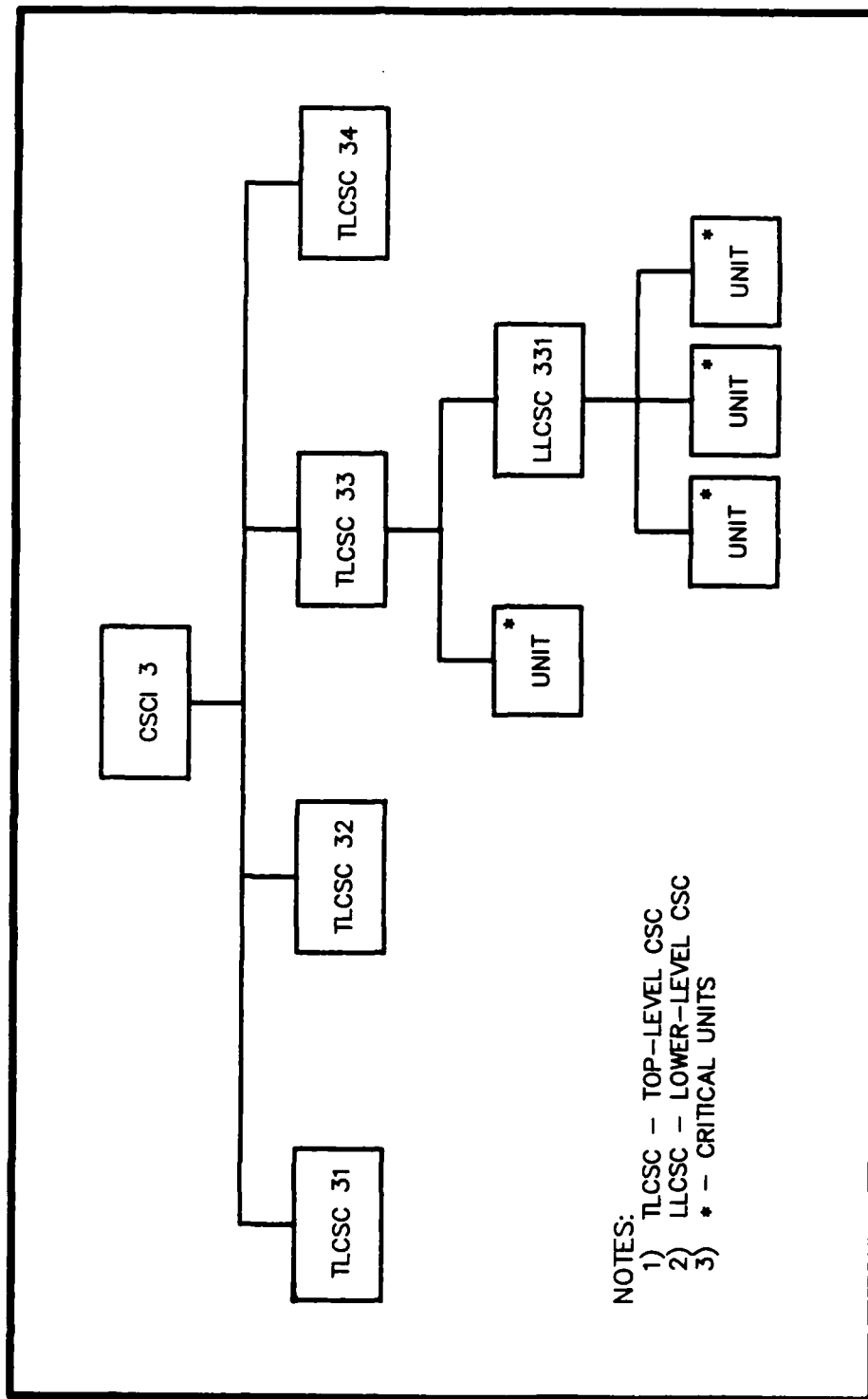
performance evaluations for numerous system candidates designed by the analyst. The analyst could continue a trial-and-error process of designing system configurations until he discovers one or more communication systems that satisfies most or all communication requirements for the relevant environment.

#### 4.1.2 Methodology of Describing the MASCOT Preliminary Design

Development of a computer simulation preliminary design should be done according to some software development standards. The structure of MASCOT's design closely adheres to the draft Defense System Software Development Standard (DoD-STD-SDS) [22]. Figure 4.1-1 provides a breakdown of how a typical computer software configuration item (CSCI) of MASCOT would be designed if the Standard were followed rigidly. Through tailoring of the CSCI architecture to meet the needs of this project, however, MASCOT's design structure has also incorporated the architecture defined in the Software Top Level Design Document (STLDD) [21], which is the DID for MIL-STD-490 software deliverables (see Figure 4.1-2), with that outlined in the draft Standard to arrive at a highly unambiguous architecture design. Using this combined architecture approach, Figure 4.1-3, MASCOT concepts and functional requirements were enumerated and organized.

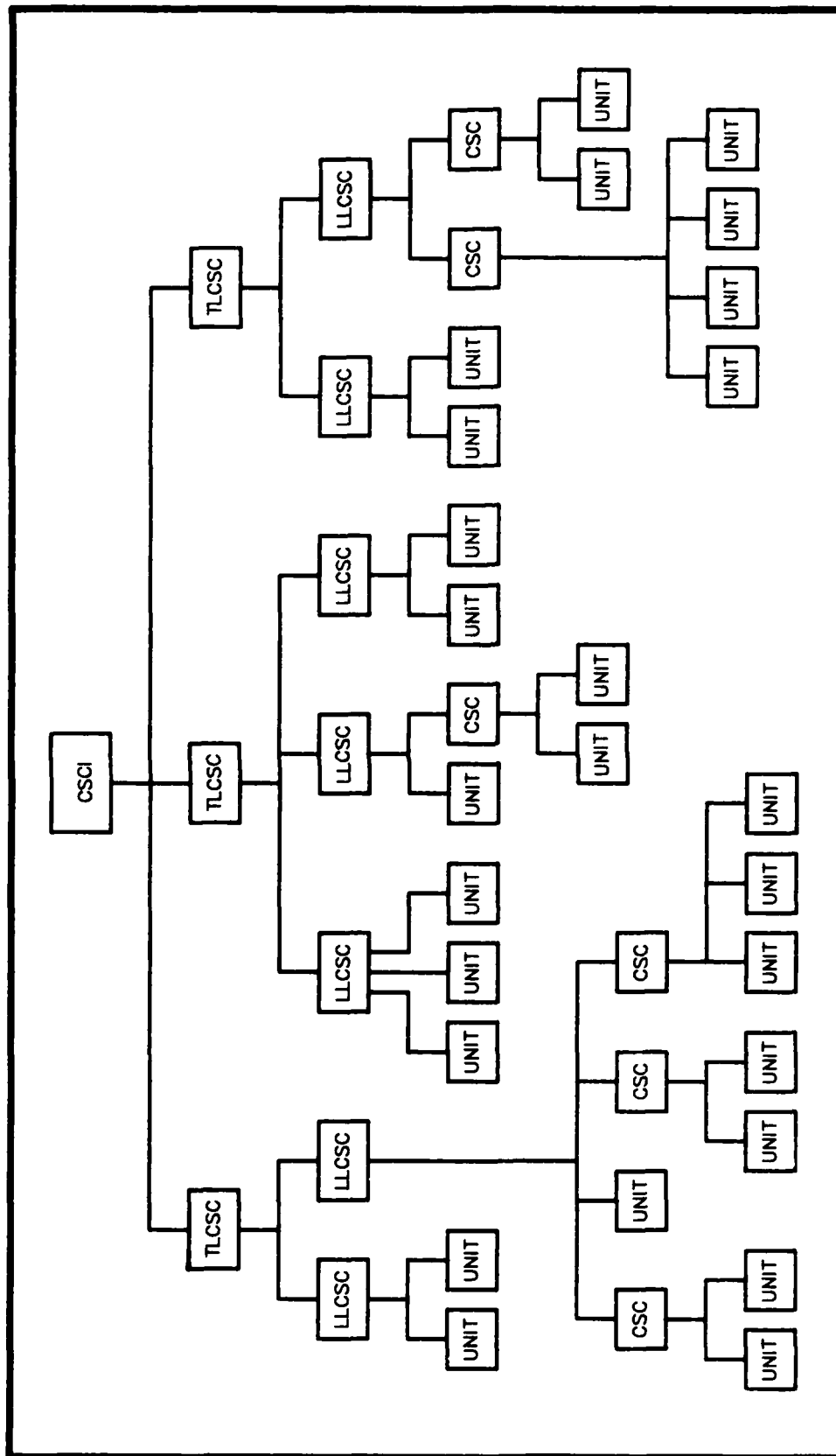
The design is a concatenation of software units functioning at various levels. The TLCSC (Top-Level Computer Software Component) is the most general component of the design structure, responsible for performing a large number of logically related functions that, taken together, comprise a subset of the overall functional requirements of MASCOT. Each function for which a TLCSC is responsible can be divided into several logically related subfunctions, each of which would be executed within a next level unit, the Low-Level Computer Software Component (LLCSC). If a function to be performed by an LLCSC still is too broad, it too can be divided into a group of logically related subfunctions, and these subfunctions all would be performed within the one CSC (Computer Software Component). When a function is no longer divisible, it is assigned to a UNIT, the lowest level logical entity of the design structure and hence the fundamental building block of MASCOT. All code produced to implement a unit can be tested independently, even with respect to units residing within the same upper level component.





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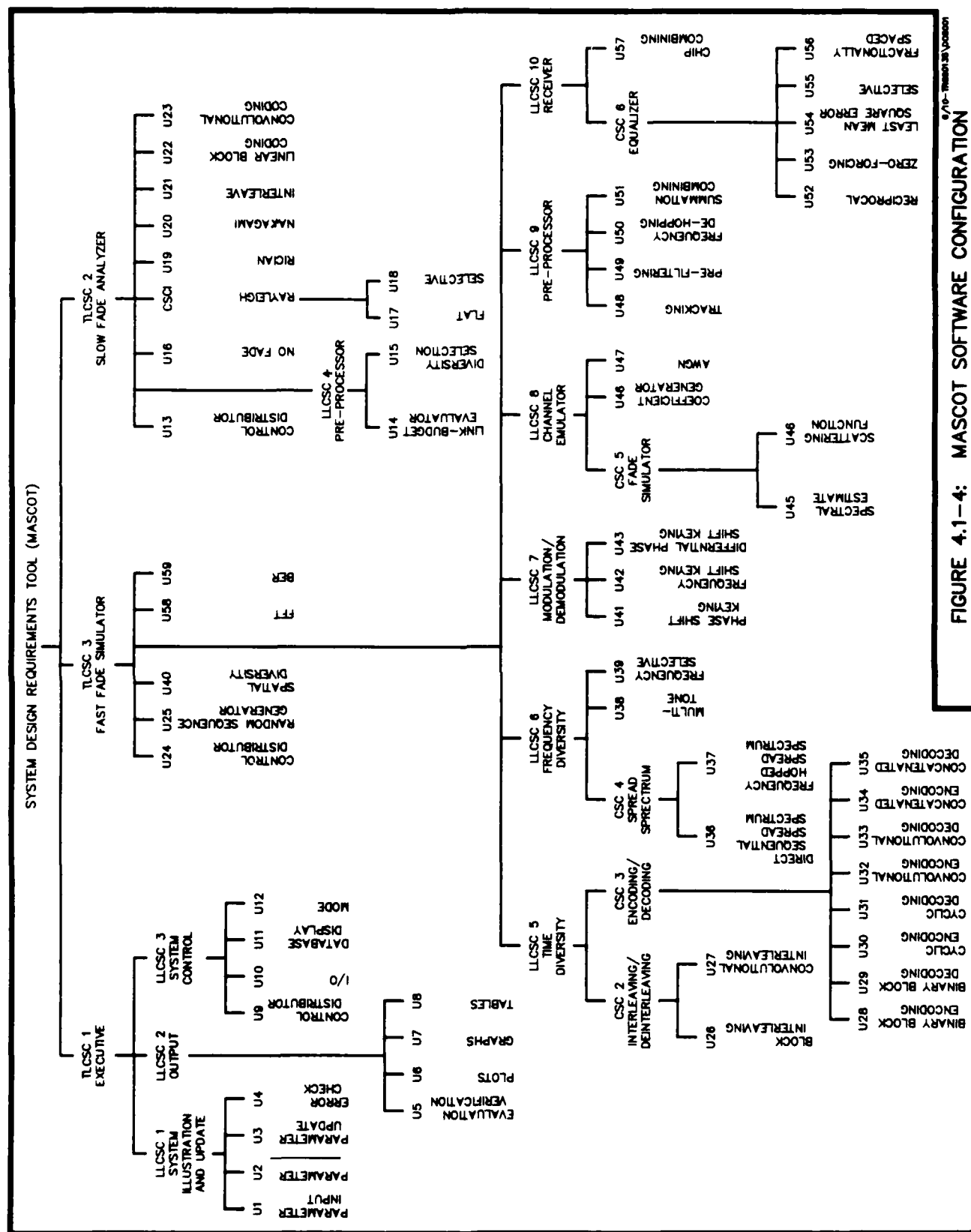
FIGURE 4.1-2: SAMPLE CSCI ARCHITECTURE ACCORDING TO STLDD  
(REFERENCE MIL-STD-490)



9/10-TH8801.35\005000

FIGURE 4.1-3: SAMPLE "COMBINED" CSCI ARCHITECTURE DIAGRAM

Figure 4.1-4 shows the Phase I MASCOT design; it will be composed of three TLCSC'S, ten LLCSC's, six CSC'S, and fifty-nine units. In the sections immediately following, each MASCOT component is described in detail. Because the decomposition of MASCOT's design structure was based on functional requirements, component descriptions consist of the purpose and functional goals of the module, with minimal reference as to how the module relates operationally to other MASCOT components. These component descriptions alone cannot provide the reader with an effective understanding of the execution organization of MASCOT; to remedy this, three execution flow diagrams have been developed for the three TLCSC's; the executive (overall operation of MASCOT), the slow fade analyzer and the fast fade simulator, respectively. These diagrams depict execution flow not only visually, but also via accompanying text summaries of component actions. Each diagram appears at the beginning of the section it describes: 4.2, Executive; 4.3, Slow Fade Analyzer; and 4.4, Fast Fade Analyzer.



## 4.2 TLCSC1 (EXECUTIVE)

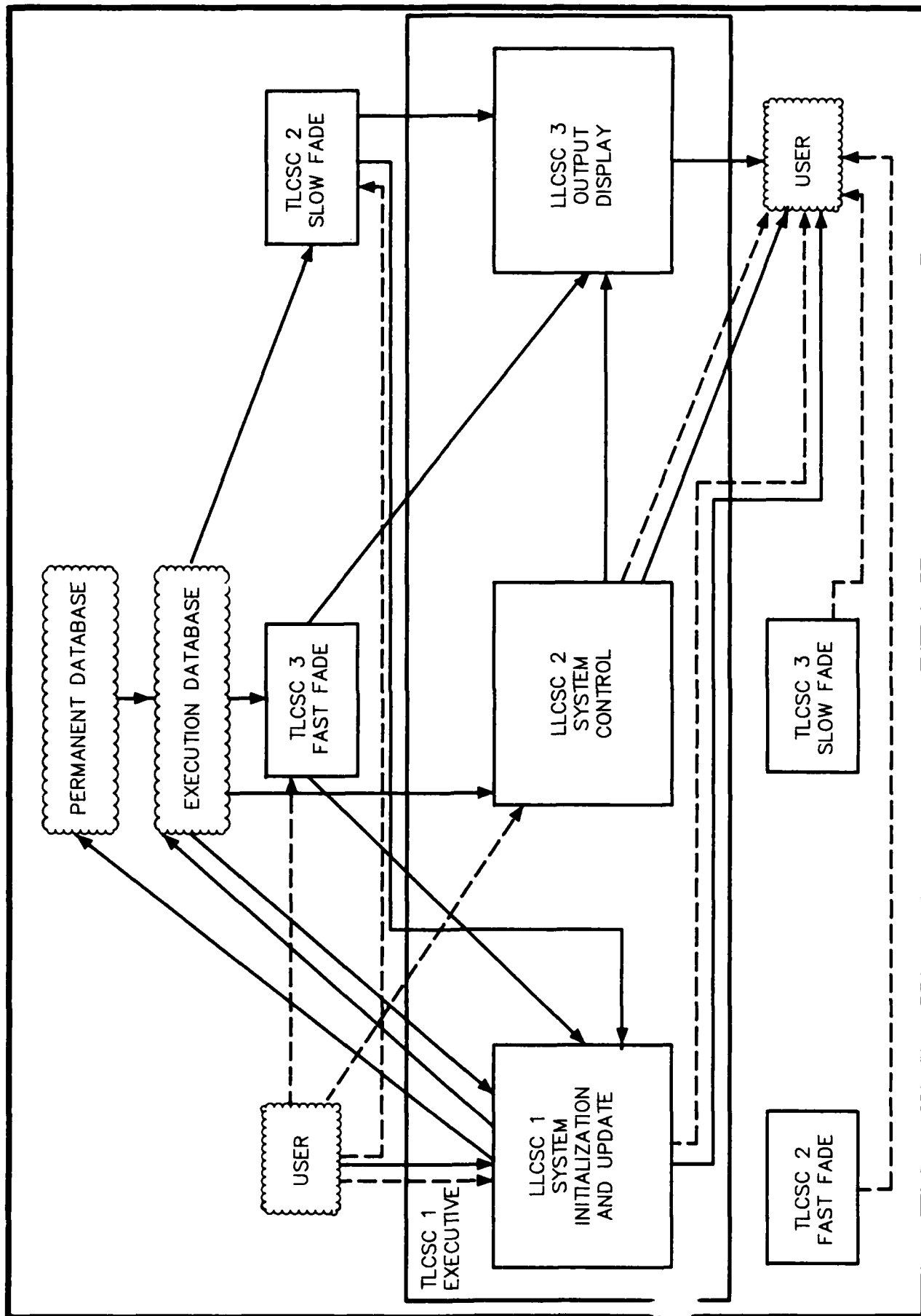
The primary component of the system design requirements tool (MASCOT) is the executive module, represented by TLCSC1. The executive performs two crucial functions: it directs input/output (I/O) operations and provides the execution cycle control mechanism.

I/O operations are facilitated via an interface between the user and the tool through which the user may enter initialization parameters, review the system database, revise parameter values, and view the results of the link evaluation in the format of his choice. The control mechanism monitors the execution cycles of the tool and ensures its proper operation. Figure 4.2-1 shows the flow of the overall operation of MASCOT. A functional diagram of the executive is shown in Figure 4.2-2. It consists of three LLCSC's, each of which is described in the sequel.

### 4.2.1 LLCSC1 (System Control)

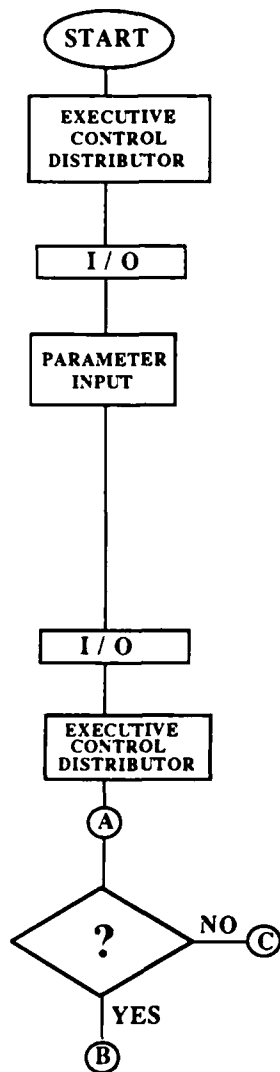
LLCSC1, the system control component, regulates the operational flow of the system design requirements tool. The component consists of four control modules: executive control distributor, mode selector, I/O selector, and database display. The individual control modules enable the corresponding execution modules, which then perform the relevant tasks.

The executive control distributor selects the appropriate control module or link evaluator based on the current stage of the tool's execution cycle. The mode selection module performs calculations to determine the number of fade modes (fast Rayleigh, slow Rayleigh, slow Rician, etc.), as well as the length, or time-segment, of each mode. The executive control distributor will enable either the fast fade simulator or the slow fade analyzer depending on the mode selector calculations. The I/O selection module activates the appropriate unit (amongst the parameter input, parameter revision, parameter update, error check, evaluation verification, and formatted output display modules), depending on the current status of the execution cycle. The database display module allows the user to view a single execution database value, any combination of



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FIGURE 4.2-1: TLCSC 1 FUNCTIONAL DIAGRAM



When the user chooses to run MASCOT, the executive control distributor will be enabled.

The executive control distributor calls the I/O control module, because the user may wish to supply MASCOT with initial parameter values for each system link.

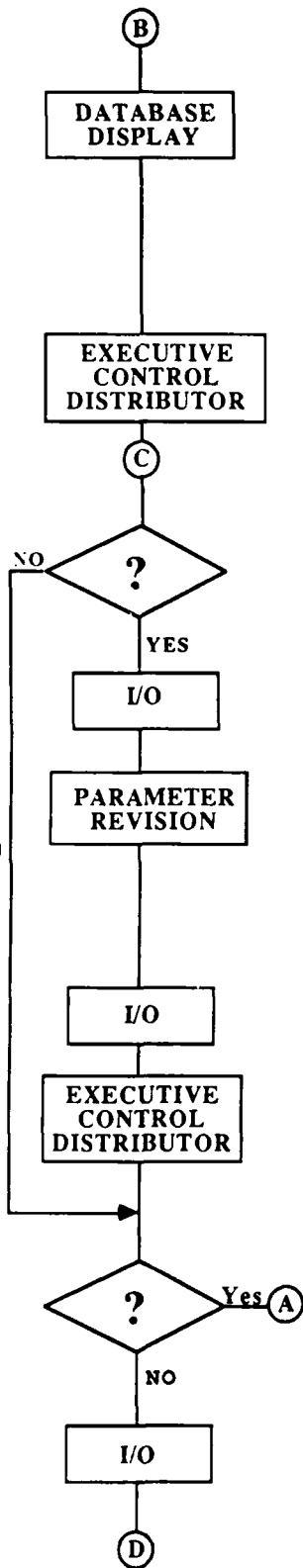
The I/O module calls the parameter input unit, within which the user defines the number of links in the communications system. He also may choose to define zero or more initial parameter values for each system link. For each system link, any parameters not given initial values by the user will be assigned default values from the corresponding location in the permanent database resident within MASCOT. Initial parameter values for each link (either assigned by the user or by default) will be stored in the execution database.

The I/O unit regains active status after each system link has been supplied with values for all parameters.

The executive control distributor regains active status after the I/O unit regains active status.

Does the user wish to view any part, or all, of the execution database?

FIGURE 4.2-2: OVERALL OPERATION OF MASCOT



The executive control distributor calls the database display unit which automatically activates the database display menu. This menu gives the user the option to view any single execution database value, the group of values for one system parameter (over all link segments), the group of values just updated internally by MASCOT, the group of values for any one segment of any link, the group of values for all segments of any one link, or the entire execution database.

The executive control distributor regains active status after the user has displayed any part, or all, of the execution database.

Does the user wish to revise any data residing within the execution database?

The executive control distributor activates the I/O control module, because the user wishes to alter execution database value(s).

The I/O module calls the parameter revision unit, within which the user may change the value(s) of one(or more) execution database location(s), excluding locations that contain values for the second, third, etc., time segment of a link. When the user changes the value(s) of location(s) within the first segment of a link, the values of parameters for all other time segments of the link subsequently will be altered internally.

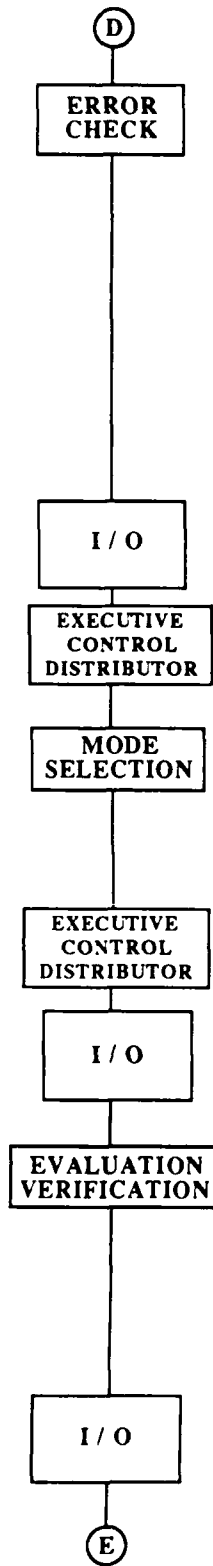
The I/O control module regains active status after the user has completed all desired execution database alterations.

The executive control distributor regains active status immediately after the I/O unit regains active status.

Does the user wish to repeat the execution database display /revision cycle (or any part of it)?

The executive control distributor activates the I/O control module to allow for execution database value(s) to be checked for syntactical and functional errors before the simulation timeperiod division, mode selection, and link evaluation processes are enabled for the system link under consideration.

FIGURE 4.2-2: OVERALL OPERATION OF MASCOT (Cont'd)



The I/O module calls the error check unit to examine execution database value(s) for syntactical and functional errors. The first time the error check unit is enabled, it will automatically check all execution database values for syntactical and functional errors. For subsequent activations of this unit, the user can choose which values will be tested. (Values within the second, third, etc., time segments of a link need not be tested. If the values for the first segment all other time segments will have valid values because they are either computed internally from first time segment values or are inherited directly from the first segment. Likewise, if the first segment contains an invalid value, all other time segments will have one (or more) invalid value(s).) The user must correct all syntactical errors detected by this unit; functional errors will produce warning messages which may go unheeded.

The I/O control module regains active status after the error check module has examined execution database value(s) for syntactical and functional errors.

The executive control distributor regains active status after the I/O module regains active status.

The executive control distributor calls the mode selection control module. This module analyzes parameter values for the system link to be evaluated, taking into consideration the length of the simulation timeperiod, and uses this information to compute the number of time segments into which the timeperiod should be divided, the length of each time segment, and the fading environment within which the link should be placed for each time segment.

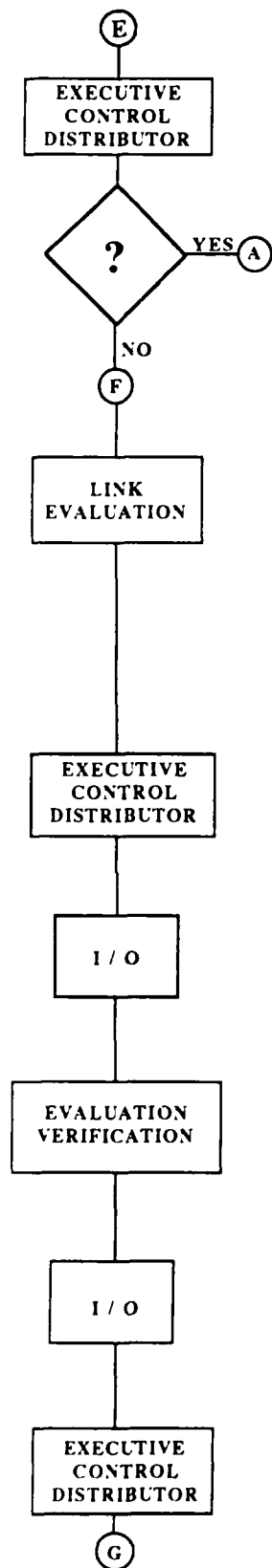
The executive distributioncontrol regains active status after the simulation timeperiod division and mode selection processes have been completed for the system link to be evaluated.

The I/O control module is called by the executive control distributor to enable the presentation of mode selection module results.

The I/O module enables the evaluation verification unit, which will display all values computed by the mode selection module for user verification. The user clearly will be able to see the number of time segments the current link requires, the length of each time segment, and the fading environment, deemed optimal by MASCOT, within which the link will be evaluated (for each time segment).

The I/O control module regains active status after the user has been presented with all mode selection results.

FIGURE 4.2-2: OVERALL OPERATION OF MASCOT (Cont'd)



The executive control distributor regains active status immediately after the I/O unit regains active status.

The user has viewed mode selection module results. Is he dissatisfied enough with these results to want to revise parameter values for the current link (by revising values resident in first time segment execution database locations for this link) and have MASCOT re-enable the simulation timeperiod division and mode selection processes?

The executive control distributor calls either the fast fade control distributor or the slow fade control distributor to evaluate the current link for the current time segment. The control distributor to be enabled will be determined based on the value calculated by the mode selection module for the current time segment of the current link.

See Figures 4.3-1 and 4.4-1 for detailed flow diagrams of the slow fade analyzer and the fast fade simulator, respectively.

The executive control distributor regains active status after the current link has been evaluated for the current time segment in the fading environment dictated by the mode selection module.

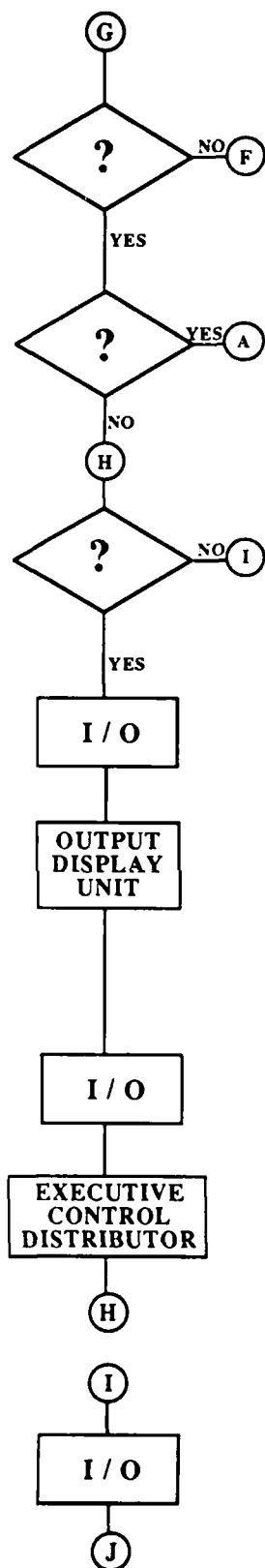
The executive control distributor calls the I/O control module, because the results computed by either the fast fade simulator or the slow fade analyzer for the current time segment of the current link must be presented to the user.

The I/O control module enables the evaluation verification unit, which will display all values computed by either, the fast fade simulator or the slow fade analyzer for the users inspection. Performance results for the current time segment of the current link will be presented in an unstructured format.

The I/O control module regains active status after the user has been presented with performance evaluation results for the current time segment of the current link.

The executive control distributor regains active status after the I/O module regains active status.

FIGURE 4.2-2: OVERALL OPERATION OF MASCOT (Cont'd)



Is the current time segment the last time segment defined for the current link? If not, make the next time segment the current time segment and return to the link evaluation process for the current link (with the new current time segment).

The user has viewed link performance evaluation results for all time segments of the current link. Is he dissatisfied enough with the results returned from one (or more) link time segment evaluation(s) to want to revise overall parameter value(s) for the current link and have MASCOT reinitiate the simulation timeperiod division, mode selection, and link evaluation processes for the current link?

Does the user wish to examine link performance evaluation results for all time segments of the current link in a more structured format? If so, the user will be presented with an output menu through which he can select the format in which results will appear.

The I/O control module is called by the executive control distributor, because the user has indicated his desire to view link performance evaluation results for all time segments of the current link in a structured, efficient format.

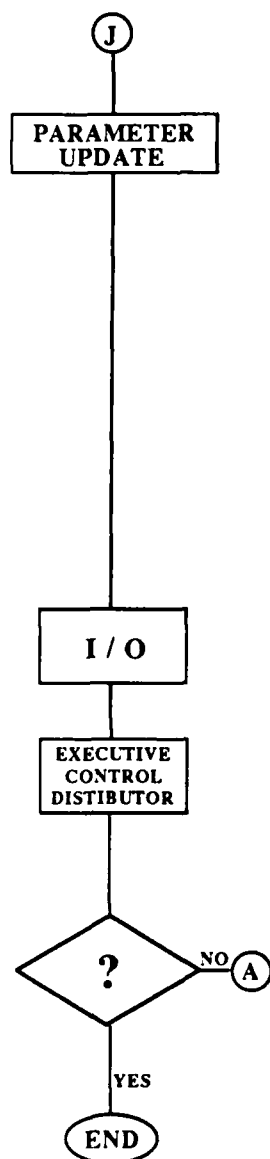
The I/O module calls the output display unit corresponding to the form in which the user wished to view performance evaluation results for the current link. Output forms from which the user may select are plot, table, or graph. Each of these output units will contain a menu through which the user can choose the variables to be included in the output analysis.

The I/O module regains active status after the appropriate output display unit has presented the user with all relevant link performance evaluation output.

The executive control distributor regains active status immediately after the I/O module regains active status. At this point, the user can choose (via the output menu) to enable an output display unit to present other relevant output analysis or he can choose to exit the output display process.

The executive control distributor calls the I/O control module, because link performance evaluation values for the current link must be saved in the execution database. The set of values to be saved for the relevant parameters will be based upon criteria specified by the user. In addition, if there are more system links to be evaluated, the parameter values of the next current link will be updated by MASCOT, based on the values just stored in the execution database for the current link.

FIGURE 4.2-2: OVERALL OPERATION OF MASCOT (Cont'd)



The I/O module calls the parameter update unit, within which link performance evaluation results for the current link will be stored in the execution database. The user is presented with the link result menu, from which the user chooses the option that will determine which set of link performance values will be saved. For each time segment of the current link, a bit error rate or a bit error probability has been computed. From the link result menu, the user can choose to save results from the time segment that provided the highest bit error rate (BER) or the highest bit error probability (BEP), the time segment that provided the lowest BER or BEP, or the time segment that provided the median BER or BEP value with respect to all time segments of the current link. If the current link is not the last system link to be evaluated, parameter values for the next current link will be updated, based on the values just saved in the execution database for the current link. The updating process is bypassed if the current link is the last link to be evaluated.

The I/O module regains active status after the link performance evaluation results for the current link have been stored in the execution database and, if possible, parameter values for the next current link have been updated.

The executive control distributor regains active status after the I/O module regains active status.

Is the current link the last link in the system to be evaluated? If not, make the next system link the current link and return to the parameter display/revision process with the new current link.

FIGURE 4.2-2: OVERALL OPERATION OF MASCOT (Cont'd)

execution database values, or the entire execution database. (The execution database contains all system parameter values necessary for successful link performance evaluation and is established in the parameter input and parameter revision modules.)

4.2.1.1 Unit 1 (Executive Control Distributor). Any interaction with the system control component automatically activates the executive control distributor. The executive control distributor, in turn, selects the appropriate control or link evaluation module based on the current phase of the tool's execution cycle. The execution cycle consists of five phases: the parameter input and revision phase, the mode selection and verification phase, the link evaluation and verification phase, the output display and storage phase, and the system update phase. The executive control distributor will be reactivated after completion of each execution task that it has initiated.

The executive control distributor activates the parameter input module via the I/O control module to perform the first significant execution task. This task, which initiates the parameter input and revision phase of the execution cycle, entails the transcribing of the default parameter value set from the permanent system database to the execution database. This copying process is repeated for each system link (as well as for each mode time-segment per link, if there is more than one for a link). For each system link, in addition, the user is given the opportunity to enter initial parameter values that differ from the default values inherited from the permanent database.

After all initial values have been entered into the execution database, the executive control distributor will activate the database display control module, if the user wishes to view any part or all of the execution database. If the user wishes to revise any values residing within the execution database, the executive control distributor enables the parameter revision module via the I/O control module. Within the parameter revision module, the user may alter any execution database value.

Following the display/revision process, the I/O control module activates the error check module, which examines values in the execution database for syntactical and functional errors. Error checking is the final task performed within the parameter input and revision phase.

Upon completion of the error checking task, the executive control distributor calls the mode selection module, which will (among other duties) determine the fade type of the channel from the signal and channel initialization parameters resident in the execution database. The executive control distributor next enables the evaluation verification module via the I/O control module for displaying the results of these calculations. The actions carried out by the mode selection and evaluation verification modules comprise the mode selection and verification phase of the execution cycle.

If the user is satisfied with the mode selection calculations, the executive control distributor initiates the link evaluation and verification phase by activating the appropriate module for link (or time-segment) performance evaluation, based on the results of these calculations. If the user is not satisfied with the calculations, the executive control distributor resumes the display/revision process within the parameter input and revision phase.

Following a complete link performance evaluation, the executive control distributor selects the evaluation verification module, via the I/O control module, to present results in an unstructured format. If the user is satisfied with the link performance values, the executive control distributor then provides the user with the opportunity to redisplay the values in a more visually concise form by entering the output display and storage phase. If the results are deemed unacceptable, the executive control distributor resumes the display/revision process.

After link evaluation results have been displayed in all desired formats, the system update phase of the execution cycle is activated. Within this phase, the executive control distributor delegates the final task of the execution cycle to the parameter update module, via the I/O control module. Within the parameter update module, link performance evaluation results for the current

system link will be saved in the execution database. If the current link is not the final link to be evaluated, the channel parameters of the next link will be updated in anticipation of that link's evaluation. If all system links have been evaluated, the contents of the execution database will be saved in a permanent file for future reference. If there are more links to be analyzed, the executive control distributor resumes the display/revision process. Otherwise, the control distributor terminates execution of the tool.

It should be noted that for multi-link systems, intermediate (link) signal processing is assumed, in general, to be incorporated for evaluating system performance. However, the configurations without onboard satellite processing (in an earth-satellite-earth hop) can be investigated as well. For the latter case, the satellite would be envisioned as an ideal repeater, with perfectly linear transponders, etc. The user would indicate communications system intermediate signal processing at MASCOT initialization.

4.2.1.2 Unit 2 (I/O). Whenever the system design requirements tool needs user input; whenever execution database values are revised, updated, or checked for errors; whenever mode selection calculations or link evaluations are performed; or whenever the user wishes to have the tool display structured versions of link performance results, the executive control distributor enables the I/O control module. The I/O control module, in turn, activates either the system initialization and update component (LLCSC2) or the output display component (LLCSC3), depending on the stage of the tool's execution cycle and the task to be performed. After the execution modules within either the system initialization and update component or the output display component have completed their assigned tasks, the I/O control module will be reactivated temporarily, at which time it will signal the executive control distributor to resume active status.

At the parameter input and revision stage of the tool's execution cycle, the I/O control module calls the parameter input execution module, within which the user can enter values that will aid in the establishment of the initial execution database. The I/O control module also will call the parameter revision execution module later in the parameter input and revision stage, if

the user wishes to alter execution database values. As the final action in the parameter input and revision stage of the execution cycle, the I/O control module will enable the error check execution module to examine the values of execution database location(s) for syntactical and functional errors.

At the mode selection and verification phase and the link evaluation and verification phase of the tool's execution cycle, the I/O control module enables the evaluation verification execution module. This module provides the user with unstructured results of either mode selection or link performance calculations, depending on the execution cycle phase.

In the output display and storage phase, the I/O control module activates the output display unit(s) of the user's choice. Finally, if the tool state resides in the system update phase of the execution cycle, the I/O control module will call the parameter update execution module. This update module will save link evaluation results and may update execution database values so that the succeeding system link, if there is one, has been prepared for evaluation.

**4.2.1.3 Unit 3 (Database Display).** When the user accepts the control distributor's offer to view the execution database, the distributor will enable the database display control module. The executive control distributor extends this offer at three points in the tool's execution cycle: immediately following parameter input, immediately preceding parameter revision, and just before a new system link is to be analyzed.

Once the database control module has been activated, several options for viewing the execution database contents are presented to the user via a database display menu. The first option of the menu would allow the user to view any single system parameter for one link (taking into consideration the link's individual time-segments). The second option would allow for the study of all values of a single parameter over all links. The third option would let the user view all parameter values for one specific link. The fourth option would display all of the parameters for all of the links. The fifth option would permit the user to view those parameters which had been

internally updated, transparent to the user. Finally, the sixth option would enable the user to exit the database display control module. After execution database values are shown via one of the following options, the database display menu is redisplayed.

4.2.1.4 Unit 4 (Mode Selection). After the parameter input and revision phase of the tool's execution cycle has been completed, the executive control distributor activates the mode selection control module. The mode selection control module retrieves input parameter values from the execution database and carefully analyzes these values in order to select the appropriate system link evaluation modes sequence: fast fade simulation or slow fade analysis. Since a single link may comprise several modes (and hence mode/time-segments) as time progresses, the two evaluation modules (slow fading and fast fading) may be enabled several times for each link. The algorithm for this selection function is as yet to be determined, although much is known about it (see Sections 3.2 and 5.3.3).

The number of modes is dependent on the duration of communication and the time from burst as it influences electron density fluctuation, absorption, etc. For example, the mode sequence may undergo fast-to-slow-to-fast transitions during a message transmission if its duration is sufficiently great. In addition, variation in the fading statistics may occur with time. If there is a strong specular signal component relative to the scatter components, Rician fading may occur, for instance, as an intermediate step between a slow fade to no fade transition. Slow Rayleigh, slow Rician, and no fading conditions are all considered under the Slow Fade Analyzer component TLCSC2, and the selection of one of them is an integral part of the fade analyzer operation.

Regardless of the number of mode changes per link, all mode transition points and duration times are computed and stored by the mode selection module in the execution database. The mode selection control module then returns control to the executive control distributor. The distributor, in turn, enables the evaluation verification execution module (via the I/O control module) to display mode-related calculations, which will ensure the user that the appropriate link evaluation method has been selected. If the user is not convinced

that the proper evaluation mode has been chosen, he may indicate that he wishes to respecify parameter values, and thereby have the tool recalculate mode selection. In this case, the executive control distributor guides the tool into the parameter input and revision phase of the execution cycle. Another option available to the user at this time is to override the mode selection result and specify the mode to be used. If the user believes that the correct link evaluation mode has been chosen, the link evaluation and verification phase is initiated.

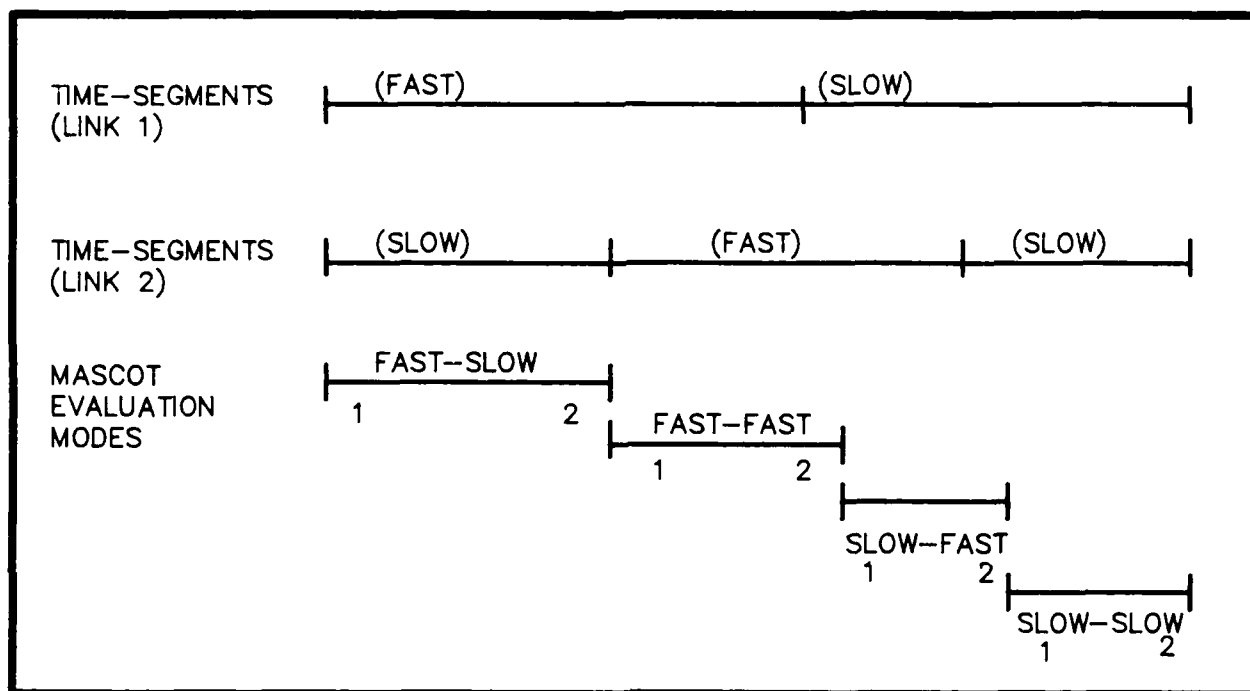
In the link evaluation and verification phase, the executive control distributor enables either the fast fade simulator or the slow fade analyzer, according to the modes determined and stored previously. Each mode choice (simulator or analyzer) will be enabled for a duration calculated (in units of bits) by

$$(\text{number of bits in simulation}) = (\text{data rate}) (\text{mode duration}).$$

For the most part, the slow fade analyzer operation is independent of message length (number of bits) since it returns a purely statistical performance measure. There are, however, slow fade cases for which simulation is needed or desired, and message length must be taken into consideration, as with the fast fade simulator, in these cases.

The preceding paragraphs take into consideration only single links and multiple links with intermediate link processing. For multi-link situations where no intermediate processing is specified, further division of the links into common intersection mode time-segments is necessary for facilitating computation (see Figure 4.2-2).

It should be noted, then, that only the slow-slow double-link and slow single-link fade combinations are evaluated by the slow fade analyzer TLCSC2. All other combinations are evaluated by the fast fade simulator, TLCSC3.



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FIGURE 4.2-2: EXAMPLE MULTI-MODE LINK

#### 4.2.2 LLCSC2 (System Initialization and Update)

LLCSC2, the system initialization and update component, was designed to provide the user with the opportunity to establish a valid execution database. In addition, this component allows the user to revise database values as he sees fit and permits internal database management, directed by the system control, to ensure optimum execution of the system design requirements tool. The system initialization and update component consists of four distinct modules: parameter input, parameter revision, parameter update, and error check.

The parameter input module enables the user to interactively specify parameter values that will define the communications system. Any parameter not interactively assigned a value by the user will be given the default value resident in the permanent database. The parameter revision module lets the user alter one or more of the system parameter value(s) residing in the execution database. The parameter update module makes changes to execution database values deemed crucial to subsequent link evaluations. The updating of execution database values is transparent to the user and must be performed to reflect changing physical conditions. The error check module operates based on user commands, and examines a single execution database value, a group of execution database values, or all execution database values for syntactical and functional errors.

4.2.2.1 Unit 5 (Parameter Input). The parameter input module is enabled by the executive control distributor via the I/O control module at the start of the parameter input and revision phase. The first act of the parameter input module is to access the permanent database resident within the system design requirements tool. The permanent database contains a default value for each of the system parameters relevant to the evaluation of a communications system subject to nuclear scintillation effects. Once the permanent database has been accessed, each value is copied into a corresponding parameter value location within the execution database. This copying process is repeated  $n$  times, where  $n$  equals the number of links in the system to be evaluated. At this point, the execution database has been established and loaded with

default values. If the user wishes to change any default value within any system link, the parameter input module will give him the opportunity to do so. Furthermore, the user will receive nominal input guidelines that will provide him with a suggested range of values for each system parameter and the system characteristics that will result for various variable value allocation options.

The parameter input module first will allow the user to alter default signal parameter values, such as bit rate and symbol duration, for each system link. Next, he may revise default values for the physical channel data, such as electron density and propagation distance, from which values for decorrelation time, coherence bandwidth, and other determinants that fix the channel mode will be calculated and entered in the execution database. If no physical channel data are altered, determinant values that fix the channel mode will not be updated internally. The user next will have the opportunity to change the values of the determinants that fix the channel mode, even if he chose not to revise any physical channel data. In this case, however, the fading channel will be emulated by an  $f^{-u}$  law spectral estimate, as opposed to a more "exact" scattering function approach. (The section for LLCSC6 discusses fading channel representation matters in more detail.) When all of the signal and channel parameters have been assigned initial values satisfactory to the user, the executive control distributor resumes active status.

**4.2.2.2 Unit 6 (Parameter Revision).** The executive control distributor enables the parameter revision module via the I/O control module to perform the optional second task within the parameter input and revision phase of the tool's execution cycle. However, the control distributor only will activate the parameter revision module when the user expresses his desire to alter parameter values within the execution database. The executive control distributor will offer the user the opportunity to revise parameter values at four points in the execution cycle: after initial system parameters have been assigned, after mode selection calculations have been performed, after link performance calculations have been performed, and after system parameter values have been updated internally. (It should be noted that revision cannot be performed after each time-segment performance evaluation unless it is the final time-segment of one link.)

As its name implies, the parameter revision module permits the user to revise execution database values. The user is queried for the location in the database that he wishes to alter and the new value to be stored in the location. The user also has the option of exiting the module, but until he exercises this option, the parameter revision module will continue asking him for the next execution database location to be revised. When the user indicates that no additional values are to be changed, the parameter revision module transfers control back to the executive control distributor.

4.2.2.3 Unit 7 (Parameter Update). The parameter update module is activated by the executive control distributor via the I/O control module to initiate the final phase in the tool's execution cycle, the system update phase. During this phase of the execution cycle, link performance evaluation values, computed for the system link being scrutinized during the link evaluation and verification phase of the cycle, are stored in the appropriate execution database locations.

If all system links have been analyzed, the execution database will be written in its entirety to a permanent auxiliary file that the user can review at any time. In addition, the executive control distributor will resume active status and will terminate execution of the system design requirements tool. On the other hand, if there exist any system link(s) that have not yet been evaluated, the parameter update module tests to determine if crucial system parameters require updating.

The crucial system parameters, namely the decorrelation time and channel coherence bandwidth, must be updated if either of the following conditions is satisfied:

1. The user has specified that a significant time lapse has occurred between link transmissions; or
2. Each system link transmission encounters a physically independent propagation path.

If neither of these two conditions is satisfied, the parameter update module assumes that multi-link propagations occur instantaneously with respect to the rate of change of the physical environment. Therefore, the module performs no parameter updating. (In the case of multiple mode/time-segments per link, parameters that need to be passed on for the evaluation of the next link can assume best-case, worst-case, or average values, as specified by the user.)

When the parameter update module completes the environment test and parameter update process, the executive control distributor is notified to resume active status. The control distributor, in turn, enables the parameter revision module to initiate the execution cycle for the next system link.

4.2.2.4 Unit 8 (Error Check). The error check module is enabled by the executive control distributor via the I/O control module to perform the final task within the parameter input and revision phase of the execution cycle. The error check module analyzes the execution database values for syntactical and functional errors. Furthermore, the module ensures that all syntactical errors it detects are corrected by the user. All functional errors detected provide the user with diagnostic warning messages; however, the module allows functional errors to go uncorrected, and the user may ignore any or all warning messages.

The first time the error check module is activated, the entire execution database is automatically examined because it has just been established (in the parameter input and parameter revision modules), and none of its values have yet been analyzed for errors. Subsequent module activations invoke selective error checking to ensure proper tool execution. Within these activations, the user is presented with six error checking options via an error checking menu. As long as the user chooses to remain in the error check module, the error checking menu will be redisplayed after the actions triggered by the selected option have been executed.

The first option of the error checking menu permits the user to choose a single execution database value to be analyzed for syntactical and functional errors. The second menu option provides for the analysis of all values of a

single parameter over all links. The third option lets the user select a specific link and checks all parameter values within that link for errors. The fourth option will enable the analysis of all values in the execution database. If the user chooses the fifth option, only those values of the execution database that have been updated internally will be scrutinized for syntactical and functional errors. The sixth and final option enables the user to exit the error check module.

During the error check, the database value first is tested for syntactical errors, such as blatant errors or type errors. Blatant errors involve the inclusion of extraneous characters within the data value, while type errors occur when an entered value is of incorrect type. When a syntactical error has been detected, the user is presented with the erroneous value and is asked to enter a valid value in its place. The new value then is tested to ensure its validity. The error check module will not continue operating until a valid value has been provided.

When the execution database value has been deemed syntactically valid, the error check module then will analyze the value to confirm that it is functionally valid. A value is functionally valid if it does not exceed established boundaries for the corresponding parameter variable. If an entry in the execution database is functionally invalid, the user will be informed of the problem via a warning message. The user may choose to ignore the warning message, or he may supply a functionally valid value to replace the invalid value. A newly entered value is then tested for both syntactical and functional validity.

When the error checker has indicated that the execution database value is syntactically valid and the user has indicated that the value is functionally satisfactory, the error check module will begin scrutinizing the next database value in accordance with the user-selected option. After the module has tested all values relevant to the user for syntactical and functional errors, the executive control distributor will be prompted to resume active status.

#### 4.2.3 LLCSC3 (Output Display)

The output display component LLCSC3 permits the user to view in detail the values generated by the mode selection calculator, the fast fade simulator, or the slow fade analyzer. The component consists of four distinct units that help the user view and effectively analyze the mode selection and link performance results.

One of the four units, the evaluation verification unit, is enabled by the system control component within the mode selection and verification phase and the link evaluation and verification phase. Depending on which phase of the execution cycle is currently active, the evaluation verification unit provides an unformatted display of the mode selection or the link performance results for the user to analyze. If the user indicates that he is satisfied with the link evaluation values, the system control component offers him the option to view the results in a more efficient form. If the user indicates that he is dissatisfied with the link performance values, or if the evaluation verification unit has been used for displaying the mode selection results, the user is not given the opportunity to view the results in alternative formats.

The remaining three output display units, the plot, graph, and table units, organize and present link evaluation data in more readable formats. The system control component ensures that the satisfactory link performance values are transcribed to the execution database, although this action need not be performed for the mode selection values.

**4.2.3.1 Unit 9 (Evaluation Verification).** The evaluation verification module is intended to be the most informative, frequently enabled unit within the output display component. This module presents the user with either the mode selection or the link evaluation results for verification, depending on the active execution cycle phase. The next procedure performed by the tool will be based on the user's appraisal of the displayed results, as well as the current phase of the execution cycle.

If the mode selection calculator values are acceptable to the user, the link evaluation and verification phase will be initiated for additional processing of the system link. On the other hand, if these values are not acceptable, the parameter input and revision phase is activated so that the user may change various parameter values before the link is reevaluated. The user will be informed that changes to specific mode/time-segments can only be made at the cost of changing parameter values for the entire link, which may result in the altering of time-segment values with which the user is satisfied.

If the user indicates that the link (or time-segment, in the case of multiple mode links) performance results are satisfactory, the executive control distributor will assume active status and direct the I/O control module to enable the formatted output display unit(s) of the user's choosing. When link performance results have been displayed in (all of) the desired format(s), the executive control distributor enables the parameter update module to save link performance results and to update system parameter values for subsequent link evaluations. If all system links have been analyzed, no parameter values need be updated. Instead, the parameter update module will write all execution database values to a permanent auxiliary file, and the executive control distributor subsequently will terminate execution of the tool.

Should the user indicate that the link performance results are unsatisfactory, the system design requirements tool provides him with the option of reevaluating the link using alternative parameter values. In order to achieve the goal of link reevaluation, the executive control distributor will activate the parameter revision module, within which the user will be given the opportunity to change any of the link parameter values. After the revised set of link parameter values have been verified as valid, the executive control distributor will activate the modules that will enable the link to be evaluated once again.

4.2.3.2 Unit 10 (Plots). The plot module of the output display component is enabled if the user expresses a desire to view the results of the link performance evaluation of the "current" link in a structured, pictorial format. The plot output would be strictly the two-dimensional abscissa vs. ordinate

(x vs. y) format, where x and y are continuous parameters. Some typical quantities (x,y) that could be used for the plot module are ( $E_b/N_0$ ,  $P_E$ ), ( $f_c$ ,  $t_0$ ), ( $R_0$ , BER), (simulation time, BER), etc. The user will enter the relevant x and y variables via the output menu resident in the executive control distributor. All desired parameter values are retrieved from the execution database. The plot will be displayed on the device from which MASCOT is being executed, and, optionally, on a peripheral plotting unit. Upon completion of plotting, the executive control distributor is reactivated via the I/O control module.

4.2.3.3 Unit 11 (Graphs). The graph module of the output display component is activated if the user wishes to view the results of link performance calculations for the "current" link, but the parameters under investigation take on only discrete values, in contrast to the "analog" data treated by the plot module. Some (x,y) quantities the user may wish to have MASCOT display in bar graph form are (diversity L,  $P_E$ ), (alphabet size M, BER), (modulation type,  $P_E$ ), etc. The user can enter the relevant x and y variables via the output menu resident within the executive control distributor. When the entire bar graph representing the values of the x and y variables for the "current" link has been presented to the user, the executive control distributor will regain active status via the I/O control module.

4.2.3.4 Unit 12 (Tables). The table module of the output display component was designed to serve as a supplement to the Plot and Graph modules. The user would choose to activate this module via the output menu to reinforce the pictorial information previously displayed by MASCOT. Tables provide precise variable values, thereby eliminating the need for the user to extrapolate the values of relevant variables from a plot or a bar graph, each of which by the nature of their predefined coordinate axis labeling tend to reduce precision. Alternatively, the user may wish to select the table module to present miscellaneous variable data sets consisting of a minimal number of data entries. In contrast to the Plot and Graph modules, which accept continuous and discrete data, respectively, the table module will allow for the display of either continuous or discrete data. The output format presented to the user would

generally consist of several columns, the first of which would contain listings of parameter titles and the rest of which would consist of parameter value sets for each of the time segments for the "current" link. For example, one row of the display may appear as

<u>Parameter</u>	<u>Time Segment 1</u>	<u>Time Segment 2</u>	....	<u>Time Segment N</u>
$P_E$	$10^{-2}$	$10^{-4}$	....	$10^{-3}$

The variables to be displayed in tabular form must be chosen by the user via the output menu resident in the executive control distributor. When the data sets for all relevant variables have been completely displayed in the output table, the executive control distributor, via the I/O control module, will regain active status.

#### 4.3 TLCSC2 (SLOW FADE ANALYZER)

The slow fade analyzer (TLCSC2) is the first of the two link performance evaluation components of MASCOT. The ultimate goal of this analyzer is to return either the analytically calculated bit error probability ( $P_E$ ) or the estimated bit error rate (BER) performance measure of signal transmission under slow fading, no fading, or other statistical conditions as determined by the system mode selection module. This analyzer is activated by the executive control distributor for those times when calculations performed within the mode selection control module satisfy the conditions for slow fading.

Link options available within the slow fade mode component include multi-hop spatial diversity, frequency diversity, and time diversity. These options may result from the transmission format, the prevailing channel conditions, or the selected receiver processing options. Diversity processing can improve the average bit error probability performance of the communications links.

Spatial diversity uses multiple, spatially separated receivers tuned to a single frequency band to combine redundant signals carrying the same information. Time diversity is realized (through a single receiver and frequency band) by discrete-time reordering of the symbol sequence (interleaving), following the insertion of bits within the information sequence for error detection/correction and/or simple repetition.

Frequency diversity is realized in several forms: Multi-tone transmission, which makes use of multiple frequency bands for carrying redundant information; spread spectrum, in which the effective increase in signal bandwidth can be exploited for frequency diversity; and frequency selective processing to resolve independently fading multipath signal components at a single receiver.

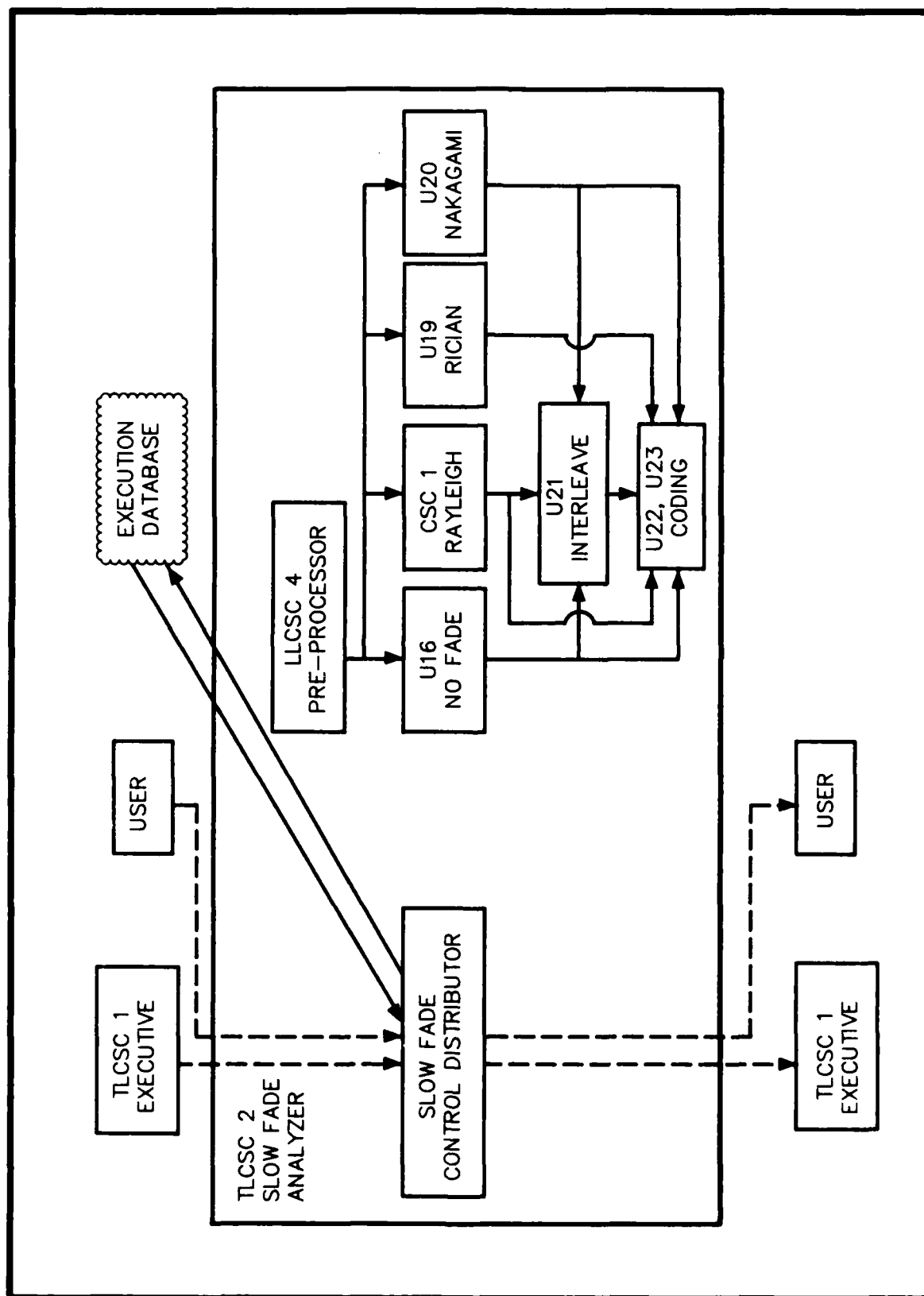
When bit error probability analysis becomes too complex, computer simulation/numerical techniques (similar to, but simpler than, those of the fast fade simulator component) will be employed to support the link performance evaluation process. The simulation will provide an estimated bit error rate (an approximation to the bit error probability) as the link performance indicator.

The most critical module of the slow fade analyzer, the slow fade control distributor, displays all signal processing options to the user in a menu and ensures the proper operation and execution sequence of the slow fade component modules. A flow chart and functional diagram of the analyzer are shown in Figures 4.3-1 and 4.3-2, respectively.

#### 4.3.1 Unit 13 (Control Distributor)

The slow fade control distributor assumes active status when the system control component enables the slow fade analyzer component, TLCSC2. When the slow fade analyzer is enabled for evaluating the first time-segment of a link, the diversity signal processing options are displayed to the user through a menu. When a top-level signal processing option is selected, one or more inner-level menus will be enabled. Each inner-level menu lists parameters that may be assigned values by the user to further describe the design of each signal processing option. Any parameter not given a value by the user will receive a default value from the execution database. In the case of multi-link systems where no intermediate link processing is performed, intermediate receiver parameters are not assigned values, and further, the double link's performance is evaluated within a single MASCOT execution cycle. It should be noted that more than one time segment combination can exist per link, as seen in TLCSC1. When the analyzer is activated for any time-segment of a link other than the first, the previously entered diversity and modulation options are used for the current time-segment performance evaluation.

The slow fade control distributor subsequently enables the execution modules relevant to the link evaluation process, based on the signal processing options chosen by the user, as well as the mode determined by the system mode selection module. The execution modules will analyze the system defined at the parameter input and revision phase of the tool's execution cycle. The slow fade control distributor will be reactivated after each execution module has completed its assigned tasks.



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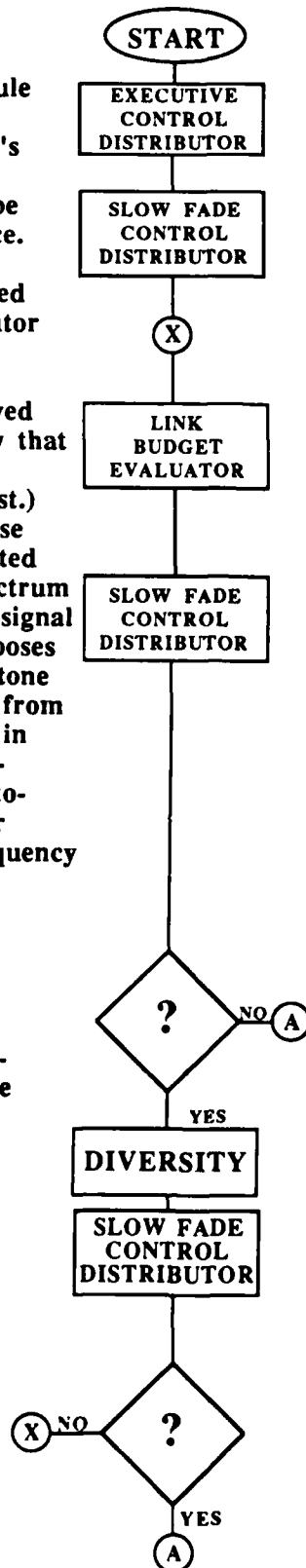
FIGURE 4.3-1: TLCSC 2 FUNCTIONAL DIAGRAM

The mode selection control module has just calculated the mode selection variable. This variable's value, in this instance, signifies that the slow fade analyzer may be used to evaluate link performance.

The link budget evaluator is called by the slow fade control distributor (sfcd) to compute the average signal-to-noise ratio, a value crucial to determining the received probability of error, the quantity that best expresses link performance when slow fading conditions exist.) An overall average signal-to-noise ratio will always be altered/updated if the user selects the spread spectrum noise reduction option from the signal processing menu. If the user chooses the spatial redundancy or multi-tone transmission redundancy option from the signal processing menu, then in addition to the average signal-to-noise ratio computation, signal-to-noise ratios will be calculated for each transmitter or for each frequency level, respectively.

Did the user select any of the frequency diversity options from the signal processing menu?

The SFCD regains active status after the diversity module has completed all frequency diversity related tasks.



The slow fade control distributor is called by the executive control distributor to monitor slow fade analysis. The user will be presented with the multi-level signal processing menu, from which he may choose signal processing option(s).

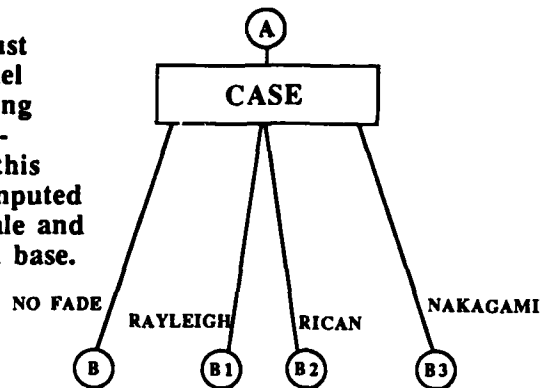
The SFCD regains active status after the link budget evaluator has computed the average signal-to-noise ratio, has altered/updated the average signal-to-noise ratio, or has calculated the average signal-to-noise ratio for a transmitter or a frequency level.

The SFCD calls the diversity unit to enable the frequency diversity option (spatial redundancy, multi-tone transmission redundancy, or spread spectrum noise reduction) selected by the user from the signal processing menu.

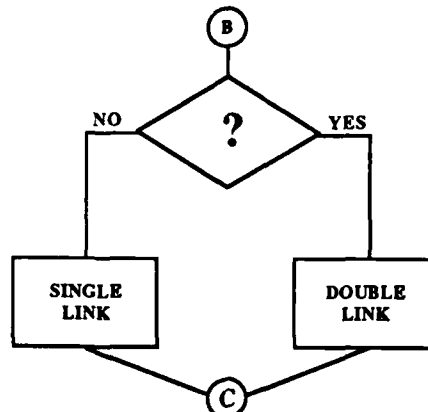
Have all required signal-to-noise ratios (requirements dictated based on the diversity option selected by the user - either spatial redundancy, multi-tone transmission redundancy, or spread spectrum noise reduction) been computed?

FIGURE 4.3-2: SLOW FADE ANALYZER

At this point, the SFCD must select the distribution model within which the slow fading environment will be represented. The SFCD makes this choice based on values computed in the mode selection module and saved in the execution data base.



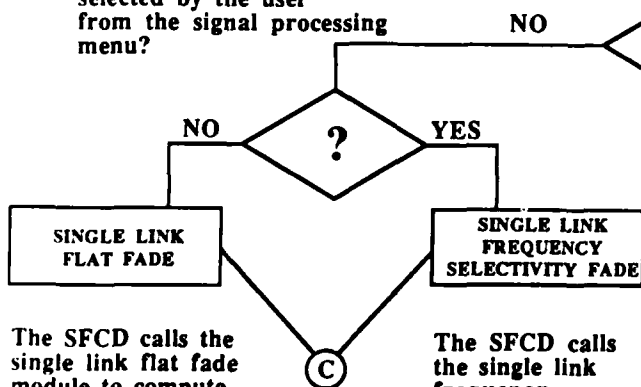
The SFCD calls the single link module to compute channel values when there is no fading or on-board processing.



Is on-board processing performed?

The SFCD calls the double link module to compute channel values when there is no fading, but on-board processing is performed

Was the frequency selectivity frequency diversity option selected by the user from the signal processing menu?



Is on-board processing performed?

Was the frequency selectivity frequency diversity option selected by the user from the signal processing menu?

The SFCD calls the single link flat fade module to compute channel fading values using formulas dictated by the Rayleigh distribution model, given that no on-board processing is performed and frequency selectivity was not chosen.

The SFCD calls the single link frequency selective fade module to compute channel fading values using formulas dictated by the Rayleigh distribution model, given that no on-board processing is performed and frequency selectivity was enabled.

The SFCD calls the double link flat fade module to compute channel fading values using formulas dictated by the Rayleigh distribution model, given that on-board processing is performed and frequency selectivity was not chosen.

The SFCD calls the double link frequency selective fade module to compute channel fading values using formulas dictated by the Rayleigh distribution model, given that on-board processing is performed and frequency selectivity was enabled.

FIGURE 4.3-2: SLOW FADE ANALYZER (Cont'd)

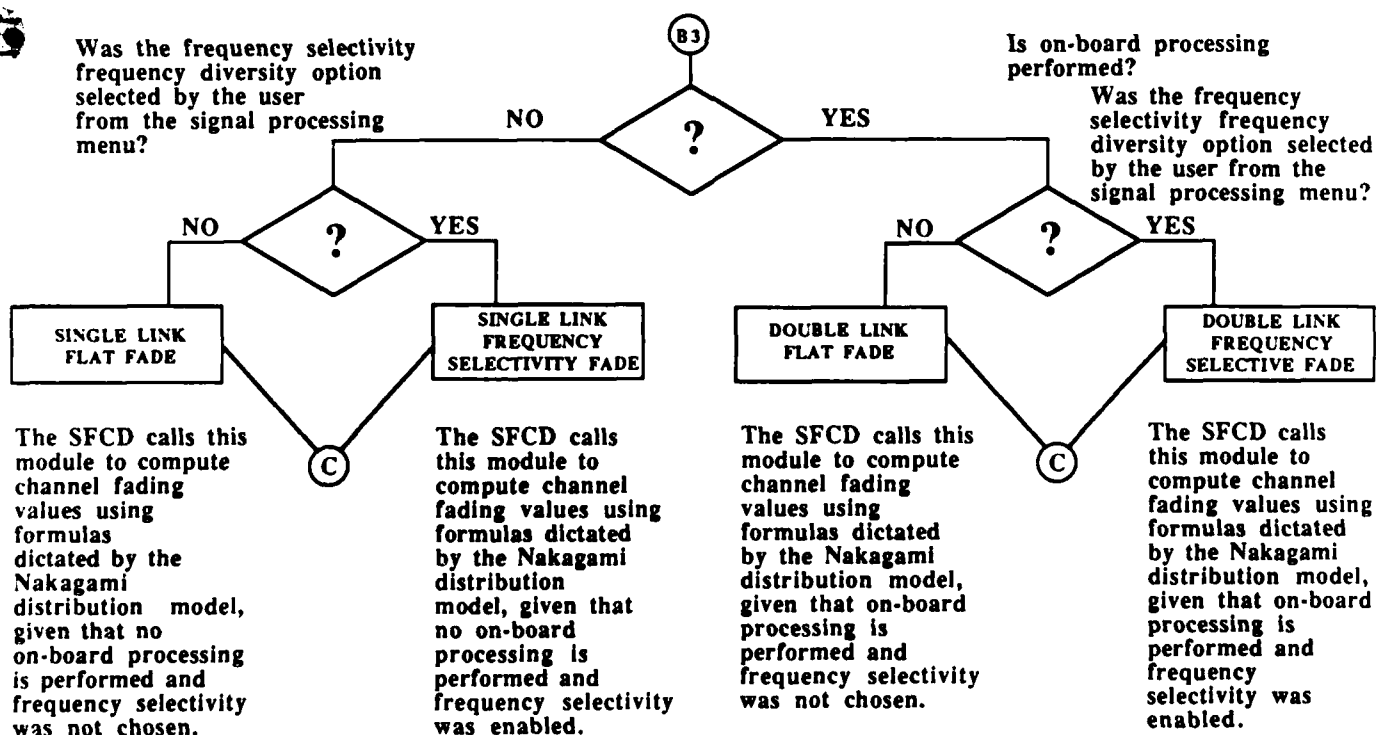
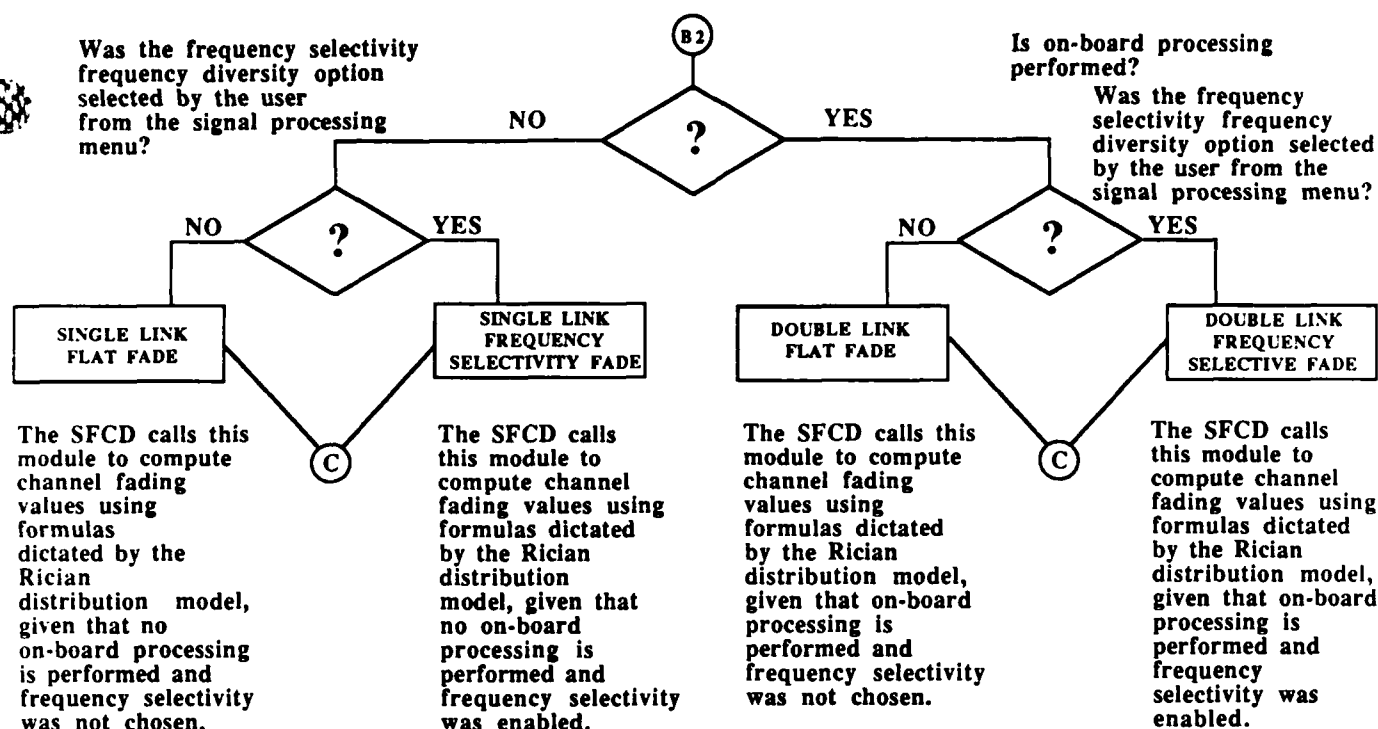


FIGURE 4.3-2: SLOW FADE ANALYZER (Cont'd)

The SFCD regains active status after the channel values have been computed, regardless of the distribution model within which the slow fading environment is represented.

Did the user select any of the time diversity options from the signal processing menu?

The SFCD calls the interleave unit to determine if the user-defined interleaver (defined via inner-level interleaving menus of the outer-level signal processing menu) has effectively randomized burst errors. In other words, is the user-defined interleaver performing acceptably, with respect to an optimal interleaver?

The user-defined interleaver has proven to be sub-optimal. Does the user wish to employ fast fade simulation to compute precise bit error rates, as opposed to bit error probability approximations that will result from the slow fade analysis because of interleaver sub-optimality?

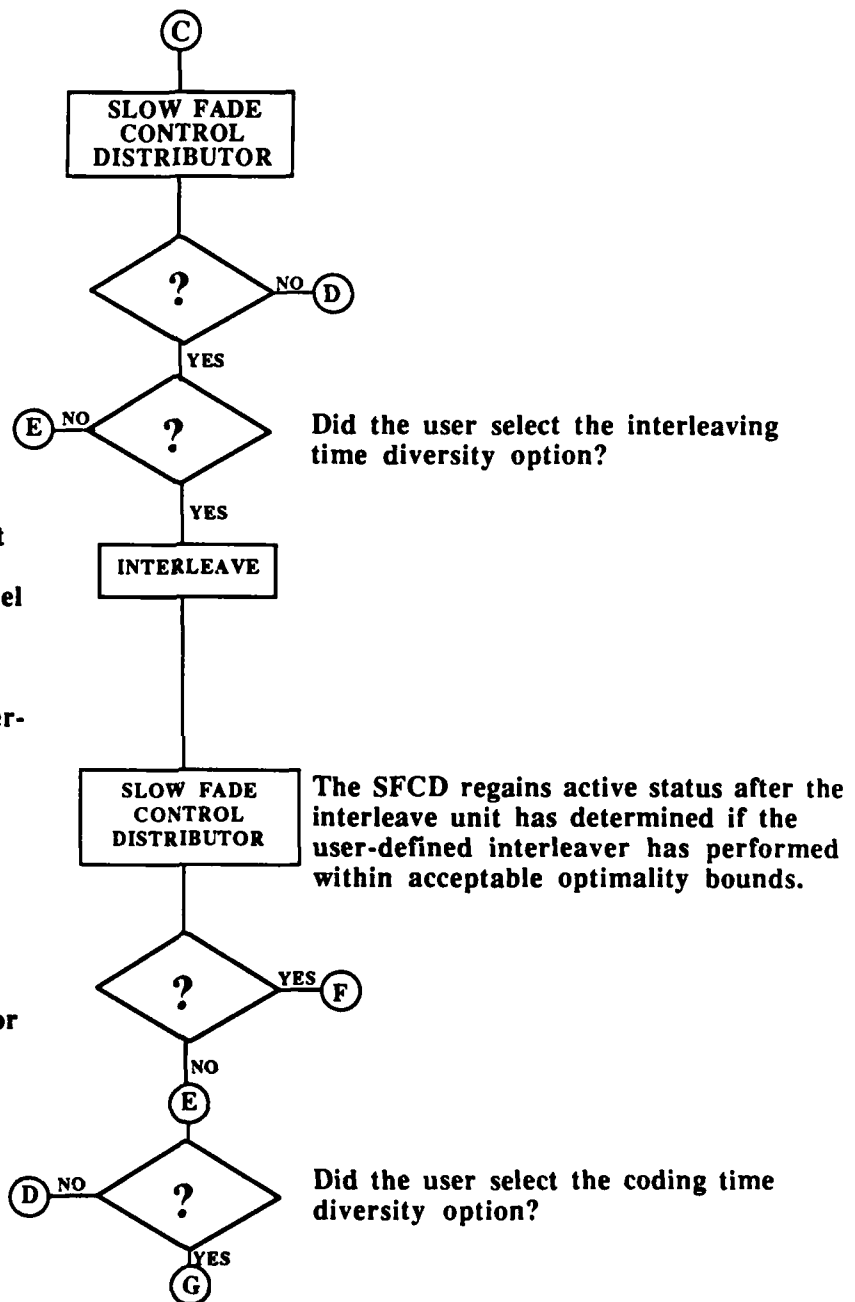


FIGURE 4.3-2: SLOW FADE ANALYZER (Cont'd)

What coding technique did the select from the inner-level coding menu of the outer-level signal processing menu?

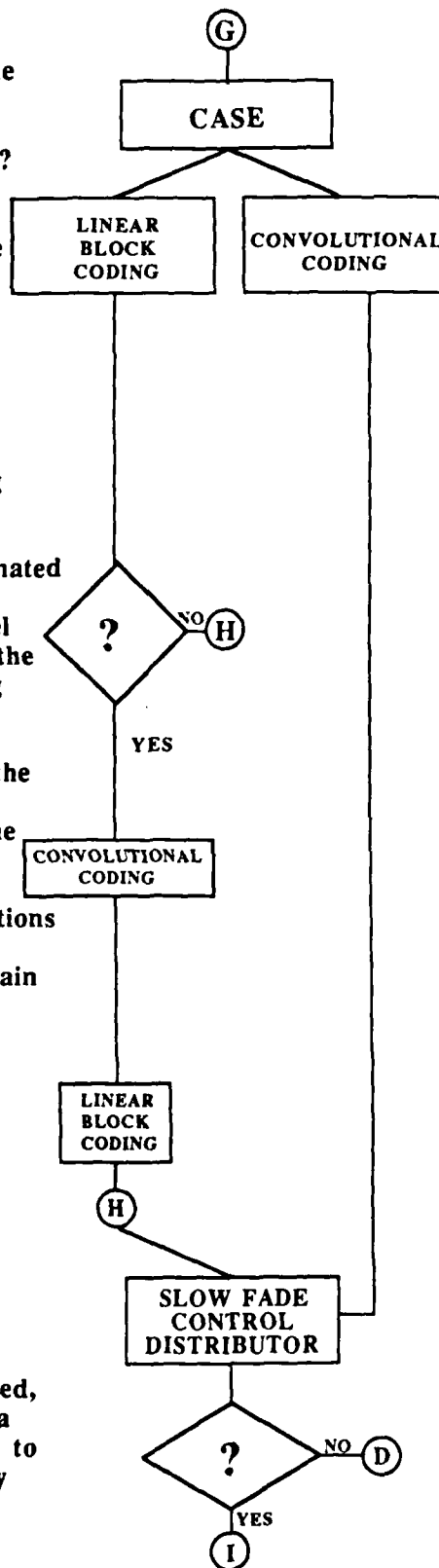
The SFCD calls the linear block coding unit to compute the decoded probability of three options: binary block coding, cyclic coding, or concatenated coding. The option is chosen by the user via the inner level linear block coding menu of the outer-level signal processing menu.

Did the user choose concatenated coding with a convolutional inner code via the inner-level linear block coding menu of the outer-level signal processing menu?

The linear coding unit calls the convolutional coding unit to serve as the inner code for the concatenated coding scheme. All values computed within this unit serve as approximations to probabilities. Fast fade simulation is required to obtain precise values.

The linear block coding unit regains control after the convolutional coding unit has computed all inner code values.

Was convolutional coding used, either by itself or as part of a concatenated coding scheme, to compute decoded probability of error approximations?



The SFCD calls the convolutional coding unit to compute the decoded probability of error via convolutional coding. However, values computed via this method serve only as error probability approximations. Precise error rates can be found through fast fade simulations.

The SFCD regains active status after all coding computations have been completed, regardless of the coding method used.

FIGURE 4.3-2: SLOW FADE ANALYZER (Cont'd)

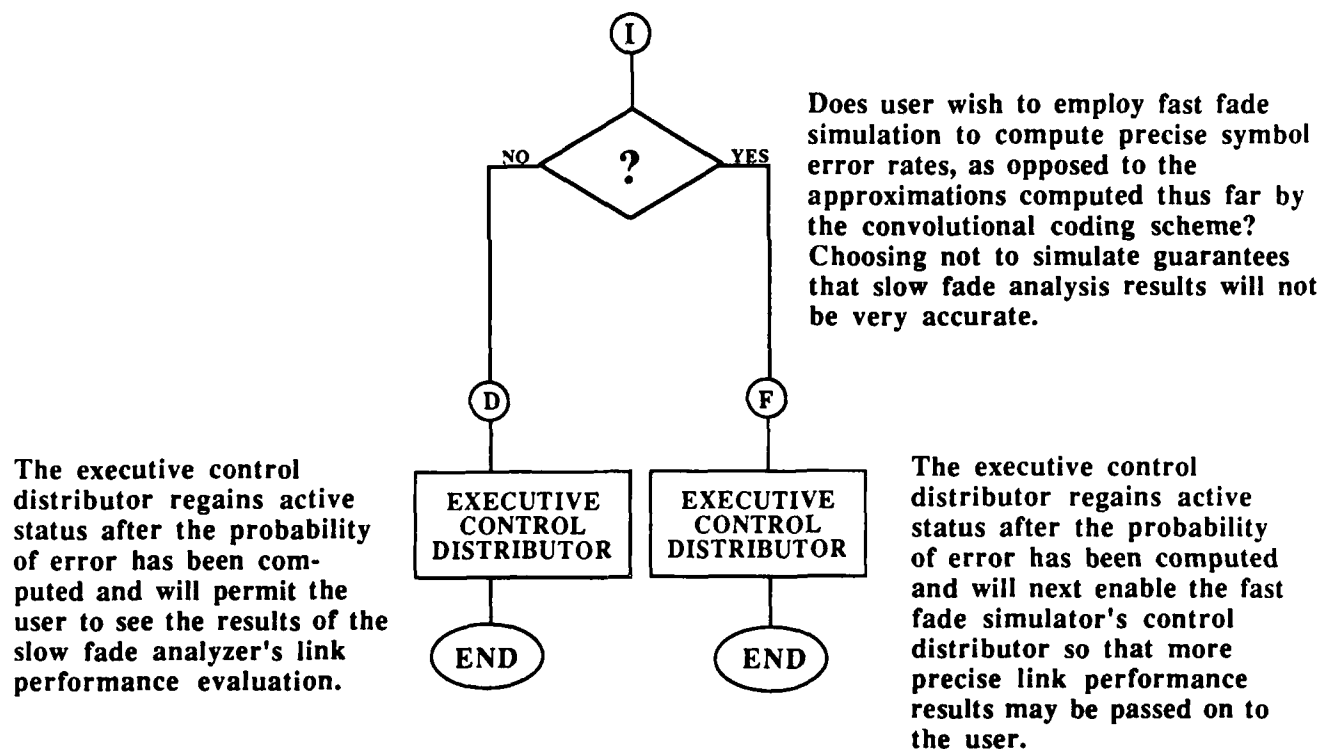


FIGURE 4.3-2: SLOW FADE ANALYZER (Cont'd)

Certain idealizations are assumed for the error probability results to be valid. Phase/frequency tracking and automatic gain control are examples of items that would be needed for proper signal demodulation. Specific idealizations are discussed within the individual module descriptions.

When link performance analysis is completed, the slow fade control distributor informs the executive control distributor to resume active status. At this point, the executive control distributor will direct the tool to display results of the analysis to the user.

#### 4.3.2 LLCSC4 (Preprocessor)

When it is activated by the executive control distributor, the slow fade control distributor first enables the preprocessor component. The preprocessor component was designed to perform two tasks. The first task involves a link budget evaluation, which computes signal-to-noise ratio for the link under analysis (see Unit 14). (A different signal-to-noise ratio value will be computed for each carrier frequency employed in multi-tone signaling schemes and for each separate path in diversity reception; these  $E_b/N_0$  values are necessary for determining the bit error probability performance measures.) The second task entails calculating additional initialization parameter values in the event that a frequency diversity option has been specified by the user.

When the preprocessor's task has been completed, the slow fade control distributor regains active status and enables the next relevant execution module, based on the time diversity options, if any, selected by the user.

4.3.2.1 Unit 14 (Link-Budget Evaluator). When activated by the slow fade control distributor, this module performs a link budget evaluation in order to compute the average signal-to-noise ratios ( $E_b/N_0$ ) for each transmitter-to-receiver signal path. The calculation of  $E_b/N_0$  is carried out by retrieving link budget parameter values from the execution database. A link budget analysis relates link parameters (whose values are resident in the execution database) to the received signal-to-noise ratio ( $E_b/N_0$ ) through the relation:

$$E_b/N_0 = P_{EIRP} G_{AR} / k T_{sys} R_D L_{FS} L_M$$

where  $P_{EIRP}$  is the effective isotropic radiated power;  $L_{FS}$  is the free space loss;  $k$  is Boltzmann's constant;  $G_{AR}$  represents the receiver antenna gain;  $R_D$  represents the data rate; and  $T_{sys}$  denotes system noise temperature; and  $L_M$  represents all other miscellaneous losses (e.g., attenuation, scattering, etc.). An  $L_{FS}$  value, and hence an  $E_b/N_0$  value, will be computed for each carrier frequency defined for the link.

When the average signal-to-noise ratio has been determined, the slow fade control distributor is reactivated.

4.3.2.2 Unit 15 (Diversity Selection). If the user has chosen to employ spatial diversity, the number of receivers ( $L$ ) and each receiver's  $(E_b/N_0)_j$  is retrieved by the slow fade control distributor from the execution database to aid in the calculations of the initial (prior to time diversity) probabilities of error. A combining algorithm will be used to yield a total  $E_b/N_0$  for the link or time segment (see Table 4.3-1 for examples of simple summation combining in the absence of fading). At this time the diversity selection module will incorporate frequency diversity options, if specified, into calculating the link/time segment  $E_b/N_0$ . If no frequency diversity has been chosen, appropriate units will be activated next (depending on executive mode selector calculations) for computing the error probability.

If multi-tone frequency has been chosen, the mutual center frequency separation will be inspected by this module. The center frequencies must be at least  $(\Delta f)_c$  apart from each other, for independence. If this condition is not satisfied, the user will be directed to input a new set of carrier frequencies.

Because of the different carrier frequencies used, as well as possibly different receiver specifications, each  $(E_b/N_0)_j$ ,  $1 \leq j \leq L$  can be distinct. Therefore, summation combining will be performed, yielding a sum  $E_b/N_0$  for use in the error probability calculation. The computational method for the error probability will have been determined, as before, by the executive mode selector module, and the corresponding analysis unit will be activated next.

TABLE 4.3-1

BIT ERROR PROBABILITIES  
 IN THE ABSENCE OF FADING ( $\gamma = \sum_1 (E_b/N_0)_i$ )

<u>MODULATION</u>	<u><math>P_B</math></u>
BPSK	$\frac{1}{2} \text{ERFC } \sqrt{\gamma}$
CBFSK	$\frac{1}{2} \text{ERFC } \sqrt{\gamma/2}$
BDPSK	$\frac{1}{2} \text{EXP } (-\gamma)$
NC-BFSK	$\frac{1}{2} \text{EXP } (-\gamma/2)$

If the user has specified frequency selective frequency diversity, the execution module verifies that selective fading is indeed valid (through the condition  $(\Delta f)_C \ll BW_S$ , where  $(\Delta f)_C$  is the channel coherence bandwidth and  $BW_S$  is the signal bandwidth). (If the condition is not satisfied, the user cannot exercise this option.) The slow fade control distributor is notified that the next module to be executed will be one of the error probability calculation units chosen depending on the channel fade as determined at the executive mode selector.

In addition to fading, if the user wishes to improve bit error performance under signal jamming conditions, he may choose to investigate spread spectrum frequency diversity. Spreading increases the effective signal bandwidth, and given a fixed level (user defined) of jamming power, a corresponding increase in the signal-to-noise ratio is obtained. The relationship between the available bandwidth and the signal-to-noise ratio is illustrated clearly by the definition of  $E_b/N_0$ :

$$E_b/N_0 = (W/J)(S/R),$$

where     S = received signal power,  
            J = noise power,  
            W = available channel bandwidth,  
            R = data rate.

After the spread spectrum signal-to-noise ratio has been calculated, the appropriate execution module, corresponding to calculations performed by the executive mode selector, is activated by the slow fade control distributor to compute the nominal bit or symbol error probabilities.

#### 4.3.3     Unit 16 (No Fade)

The slow fade control distributor enables this module during those transmission times when the system mode selector has determined that channel fading is absent. The received signal-to-noise ratio is given by the summation

$$E_b/N_o = \sum_j (E_b/N_o)_j,$$

where each  $(E_b/N_o)_j$  is the individual signal-to-noise ratio obtained through spatial diversity or multi-tone frequency diversity.

Since there is no fade present (and assuming a linear transponder) the analysis for a single link is identical to that for a double link (single hop). It should be noted that some normalizations must be performed since the uplink parameters will most likely differ with that of the downlink. With normalizations, the effective  $E_b/N_o$  to be used for calculating the hop error probability is given as a function of the uplink and downlink  $E_b/N_o$ 's:

$$(E_b/N_o)_{\text{EFF}} = \frac{\gamma_u \gamma_d}{\gamma_u + \gamma_d + 1},$$

where  $\gamma_u = (E_b/N_o)_{\text{UP}}$   
 $\gamma_d = (E_b/N_o)_{\text{DOWN}}$

Therefore, a double-link, bent-pipe system can be analytically treated as a single-link system. (It should be noted that for double-link systems with onboard satellite processing, the user only needs to execute MASCOT twice in succession, using the output of the first run as the input to the second. This is aided by MASCOT's execution database to minimize user burden.

The  $E_b/N_o$  obtained will be used to calculate the nominal link bit error probabilities, listed in Table 4.3-1 (for some common modulation schemes). The time diversity modules of Unit 21 through Unit 23 are enabled next by the slow fade control distributor after the no fade module has determined the no fade  $P_B$  corresponding to the user-specified modulation.

#### 4.3.4 CSC1 (Rayleigh Fade)

When the system mode selector has determined that the channel is in slow Rayleigh fade, the slow fade control distributor enables one of the execution modules of this component. The  $(E_b/N_o)_j$ ,  $1 \leq j \leq L$ , values, determined at the diversity module of Unit 14, are used to calculate the link transmission

probabilities of error ( $P_B$ ). Depending on the user's choice and constraining channel conditions calculated by the executive mode selector, either the flat or the selective fade module will be activated to compute the link/hop error probability.

4.3.4.1 Unit 17 (Flat Rayleigh). For single hop systems in flat Rayleigh fading, the no fade  $P_B$ 's of Table 4.3-1 are used in calculating bit error probabilities of Table 4.3-2 according to:

$$P_B(\text{fade}) = \int P_B(\text{error} | E_B/N_0) p(E_B/N_0) d(E_B/N_0),$$

where  $P_B(\text{error} | E_B/N_0)$  is the no fade bit error probability, and  $p(E_B/N_0)$  is the signal-to-noise ratio density function obtained via transformation of the Rayleigh fade distribution of the signal amplitude. Closed-form results of the integration for flat Rayleigh fading are found in Table 4.3-2. The probability of bit or symbol error equations for  $P_B$  that take into account the possible selection of the spatial diversity option for equal receiver specifications are also listed in Table 4.3-2. For distinct receiver specifications and therefore different  $(E_b/N_0)_j$ ,  $1 \leq j \leq L$ , the same relations can be used (with  $L=1$ ) by substituting  $(E_b/N_0)_1$  with  $E_b/N_0 = \sum_j (E_b/N_0)_j$ .

This execution module also calculates the probabilities of error under flat Rayleigh fade for double hop systems (single link) with no intermediate satellite processing. However, the double hop transmission is governed by different statistics: the density function characterizing the double link channel (different from the Rayleigh) is given by

$$p(A^2) = 2K_0[2\sqrt{A^2/E(A^2)}]/E(A^2),$$

where  $K_0$  is the modified Bessel function,

$A^2$  is the received signal power,

$E(A^2) = 4\sigma^4$ , and

$\sigma^2$  = variance of the underlying (Gaussian) pdf of the received signal components.

TABLE 4.3-2

SINGLE-LINK BIT ERROR PROBABILITIES (WITH SPATIAL DIVERSITY) IN RAYLEIGH FADE

MODULATIONBPSK ( $u = \sqrt{\gamma/(1 + \gamma)}$ )C-BFSK ( $u = \sqrt{\gamma/(2 + \gamma)}$ )DPSK ( $u = \gamma/(1 + \gamma)$ )NC-BFSK ( $u = \gamma/(2 + \gamma)$ )4-PSK ( $u = \sqrt{\gamma/(1 + \gamma)}$ )4-DPSK ( $u = \gamma/(1 + \gamma)$ )M-PSK ( $u = \sqrt{\gamma/(1 + \gamma)}$ )M-DPSK ( $u = \gamma/(1 + \gamma)$ )M-PSK ( $u = 2 \gamma$ )M-DPSK ( $u = \gamma$ )NC-MFSK ( $L \neq 1$ )NC-MFSK ( $L = 1$ ) $\frac{P_B}{P_B}$ 

$$\left(\frac{1-u}{2}\right)^L \sum_{k=0}^{L-1} \binom{L-1+k}{k} \left(\frac{1+u}{2}\right)^k,$$

$$\gamma = \gamma_k = \gamma_f = (E_b/N_0)_f$$

$$\frac{1}{2} \left[ 1 - \frac{u}{\sqrt{2-u^2}} \sum_{k=0}^{L-1} \binom{2k}{k} \left(\frac{1-u^2}{4-2u^2}\right)^k \right] \\ (-1)^{L-1} (1-u^2)^L \left( \frac{d}{db} \frac{1}{b} \right)^{L-1} \left\{ \frac{1}{b-u^2} \left[ \frac{\pi}{M} - (M-1) \frac{u \sin(\pi/M)}{\sqrt{b-u^2} \cos^2(\pi/M)} \right] \right\} \Big|_{b=1}$$

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$$\frac{M-1}{\left[ M \log_2 M \sin^2(\pi/M) \right] u} \\ \sum_{m=1}^{M-1} \frac{(-1)^{m+1} \binom{M-1}{m-1}^L}{(1+m+m\gamma)^L} \sum_{k=0}^{L-1} B_{k,m} (L-1+k)! \left( \frac{1+u}{1+m+m\gamma} \right)^k,$$

$$\sum_{k=0}^{L-1} \left( \frac{u^k}{k!} \right)^m = \sum_{k=0}^m B_{k,m} u^k$$

$$\sum_{m=1}^{M-1} \frac{(-1)^{m+1} \binom{M-1}{m-1}}{1+m+m\gamma}$$

The resulting probability of errors for some signal modulation schemes are presented in Table 4.3-3. (Because of complexity of analysis, the only spatial diversity option available is dual-diversity ( $L=2$ )).

4.3.4.2 Unit 18 (Frequency Selective Fade). Provided that the channel condition  $BW_s \gg (\Delta f)_C$  is valid, and the system mode selection module has determined that transmission is undergoing slow Rayleigh fade, the frequency selective fade execution module is activated by the slow fade control distributor. Because of the wideband signal, the multipath components can be resolved to provide the receiver with several independently fading signal paths. Frequency diversity on the order

$$L = BW_s / (\Delta f)_C$$

is obtained. Hence, taking advantage of this situation, the frequency selective fade module calculates the nominal selective probabilities of error ( $P_B$ ), listed in Table 4.3-4.

The  $P_B$ 's for single hop systems are derived using the no fade conditional bit error probabilities  $P_B$ , conditional on the signal-to-noise ratio ( $E_b/N_0$ ) of Table 4.3-1. (As done for the flat Rayleigh fading case, the selective fade module can calculate the error probabilities for double hop (no onboard processing) systems also, via appropriate density transformations.) Therefore,

$$P_B \text{ (selective fade)} = \int P_B \text{ (error}/E_b/N_0) p(E_b/N_0) d(E_b/N_0)$$

where  $p(E_b/N_0)$  is the signal-to-noise ratio density function obtained for the  $k$  multipaths via appropriate transformations on the joint distribution of the  $k$  signal components.

Because of the complexity of analysis, only binary PSK, NC-PSK, and DPSK signaling is considered for the frequency selective case, neglecting multiple alphabet M-ary signaling. The receiver would employ a tapped-delay-line in order to take full advantage of the diversity improvement possible by the

TABLE 4.3-3

DOUBLE-LINK BIT ERROR PROBABILITIES IN FLAT RAYLEIGH FADE

MODULATION $\underline{P_b}$ 

$$\text{NC-MFSK } (L = 1) \quad \frac{1}{2(M-1)} \sum_{K=2}^M (-1)^K \binom{M}{K} B \exp(B) E_1(B),$$

$$B = \left( \frac{K}{K-1} \right) / ((\log_2 M) \gamma); \quad \gamma = E_b/N_0; \quad E_1 \text{ is exponential integral}$$

$$(L = 2) \quad \frac{1}{2(M-1)} \sum_{K=2}^{M-1} (-1)^K \binom{M}{K} \frac{9}{[3 + (K-1) \log_2 M (\gamma/K)]} \frac{1}{[3 + 2(K-1) \log_2 M (\gamma/K)]}$$

$$\text{DPSK } (L = 1) \quad \frac{\exp(1/\gamma) E_1(1/\gamma)}{2\gamma}, \quad \gamma = E_b/N_0; \quad E_1 \text{ is exponential integral}$$

$$(L = 2) \quad \frac{9}{2(3+\gamma)(3+2\gamma)}$$

$$\text{BPSK } (L = 1) \quad \frac{1}{2} \int_0^\infty u K_0(u) \operatorname{erfc}(\sqrt{\gamma}) u/2 \, du,$$

$K_0$  is modified bessel function;  $\gamma = E_b/N_0$ .

$$(L = 2) \quad \frac{1}{2} + \frac{1}{2} (1 + 3/\gamma)^{-1/2} - (1 + 3/2 \gamma)^{-1/2}$$

TABLE 4.3-4

## FREQUENCY SELECTIVE RAYLEIGH FADE BIT ERROR PROBABILITIES

MODULATIONP<sub>B</sub>

$$\left. \begin{array}{l} \text{BPSK } (p = -1) \\ \text{C-BFSK } (p = 0) \end{array} \right\} \left\{ \begin{array}{l} \left(\frac{1}{2}\right) \sum_{k=1}^L B_k \left[ 1 - \sqrt{\frac{\gamma_k (1-p)}{2 + \gamma_k (1-p)}} \right], \gamma_k \neq \gamma_i; \\ B_k = \prod_{\substack{i=1 \\ i \neq k}}^L \left( \frac{\gamma_k}{\gamma_k - \gamma_i} \right), \gamma_k = (E_b/N_0)_k \end{array} \right.$$

$$\text{DPSK} \quad \frac{1}{2^{2L-1}} \sum_{m=0}^{L-1} b_m \sum_{k=1}^L \left( \frac{b_k}{\gamma_k} \right) \left( \frac{\gamma_k}{1 + \gamma_k} \right)^{m+1},$$

$$b_m = \sum_{n=0}^{L-1-m} \binom{2L-1}{n};$$

$$B_k = \prod_{\substack{i=1 \\ i \neq k}}^L \left( \frac{\gamma_m}{\gamma_k - \gamma_i} \right); \gamma_k = (E_b/N_0)_k$$

selectivity condition. The time diversity module(s) (Unit 1 through Unit 23) corresponding to the options chosen by the user would be enabled next by the slow fade control distributor.

#### 4.3.5 Unit 19 (Rician)

The Rician fade component is enabled primarily for those times when a strong specular component emerges from the various scatter components. Therefore, fading is still present but is no longer adequately described by Rayleigh statistics. The Rician distribution is given by

$$p(A) = \frac{A}{2\pi\sigma^2} e^{-\frac{(A^2 + E(A)^2)}{2\sigma^2}} I_0 \left[ \frac{A E(A)}{\sigma^2} \right], \text{ and}$$

the nominal bit error probability in Rician fade is given by the integration

$$P_B (\text{Rician}) = \int P_b (\text{error}|E_b/N_0) p(E_b/N_0) d(E_b/N_0),$$

where  $P_b (\text{error}|E_b/N_0)$  are those found in Table 4.3-1 and  $p(E_b/N_0)$  is the density of the received signal-to-noise ratio. As with the Rayleigh fade case, the Rician fading phenomenon can be described either as "flat" or as "frequency selective". In addition, for the purposes of MASCOT analyses, each of the two fade types is further divided into single hop and double hop systems.

Because of the analytical complexity, however, closed-form error probability expressions, such as those of Tables 4.3-1, 2, 3 and 4, cannot be easily obtained, and therefore corresponding analysis modules to Units 17 and 18 for Rayleigh fading do not exist. Instead, numerical integrations are performed (real time operation) in order to calculate the nominal error probabilities  $P_B$ , taking into consideration the appropriate  $p(E_b/N_0)$  density given flat or selective fade and single or double hop system, as well as the modulation scheme. These nominal  $P_B$ 's will be used in conjunction with the time diversity modules (if any specified), to determine the overall link performance.

4.3.6 Unit 20 (Nakagami)

The Nakagami module is enabled for those transmission times when fading other than Rayleigh or Rician is present. It can be used to approximate diversity combining results as well. The Nakagami m-distribution model described in this module depicts the slow fading channel in a more general sense, with the Rayleigh model being one special case. The m-distribution is defined, with m as a variable parameter and A as the signal amplitude, by

$$p(A) = 2m^m [\Gamma(m)]^{-1} E(A^2)^{-m} (A^{2m-1}) \exp[-mA^2/E(A^2)].$$

Appropriate adjustments of the parameter m will yield distributions ranging from Gaussian to Rayleigh to higher order densities. Regardless of the value that the executive control distributor has assigned to m (depending on the mode type), transformation of the variables of the fixed-m Nakagami distribution result in the m-distribution as a function of the signal-to-noise ratio. The signal-to-noise ratio distribution can then be used with the conditional (on the signal-to-noise ratio) probability of error expression for the user specified modulation scheme in order to determine the nominal probability of error  $P_B$ .

The non-trivial integration

$$P_B = \int P_B(\text{error}|E_b/N_0) p(E_b/N_0) d(E_b/N_0),$$

yields the nominal probability of error.  $p(E_b/N_0)$  is the probability density function of the received signal-to-noise ratio, and  $P_B(\text{error}|E_b/N_0)$  is the conditional error probability for the modulation scheme selected by the user, as found in Table 4.3-1, and also takes into account single and double hop systems.

For most choices of m, analytical complexity prohibits closed-form evaluation of nominal bit error probabilities  $P_B$ . (Closed form expressions are available for the  $m=1$  Rayleigh distribution, however, and are listed in Tables 4.3-2 and 4.3-3). When m is different from unity, numerical methods will yield the

desired  $P_B$ 's, as well as the conditional error probabilities necessary for this integration in non-binary signaling cases, as was the case with Rician fading.

Once the overall, nominal bit error probabilities ( $P_B$ 's) have been determined for the  $m$ -distributed channel and specific modulation scheme, the analytic procedures of the time diversity modules (described in Units 21 through 23) can be enabled to determine total link performance.

#### 4.3.7 Unit 21 (Interleaver)

After the nominal  $P_B$ 's have been calculated via either the frequency selective or flat fade modules, the slow fade control distributor activates the interleaver module, if the user has specified interleaving via the time diversity signal processing menu option. The effectiveness of the user-specified interleaver is compared to that of the ideal interleaver with respect to interleave time. The ideal interleaver time is defined by

$$I_L(\text{opt}) = B/R = 10\tau_0 \ln[(1-\exp(A^2/2))/U],$$

where

- $B$  = number of bits interleaved,
- $R$  = bit rate,
- $\tau_0$  = average channel fade duration,
- $A$  = signal level margin (below level without scintillation),
- $U$  = probability of time signal level is below  $A$  and fade time exceeds  $10\tau_0$  (Figure 4.3-3).

These interleaver parameter values all are retrieved from the execution database.

The effectiveness of the user-defined interleaver can be determined by extrapolation from plots such as the one shown in Figure 4.3-4. In the case where the user-defined interleaver is sub-optimal (shorter than the range of  $I_L$  values deemed acceptable by the user for reasonable burst error randomization), the user will be informed that the  $P_B$ 's that were previously calculated, as well as all subsequent bit error probabilities, are lower bounds -- the actual probability of error will be worse to some degree.

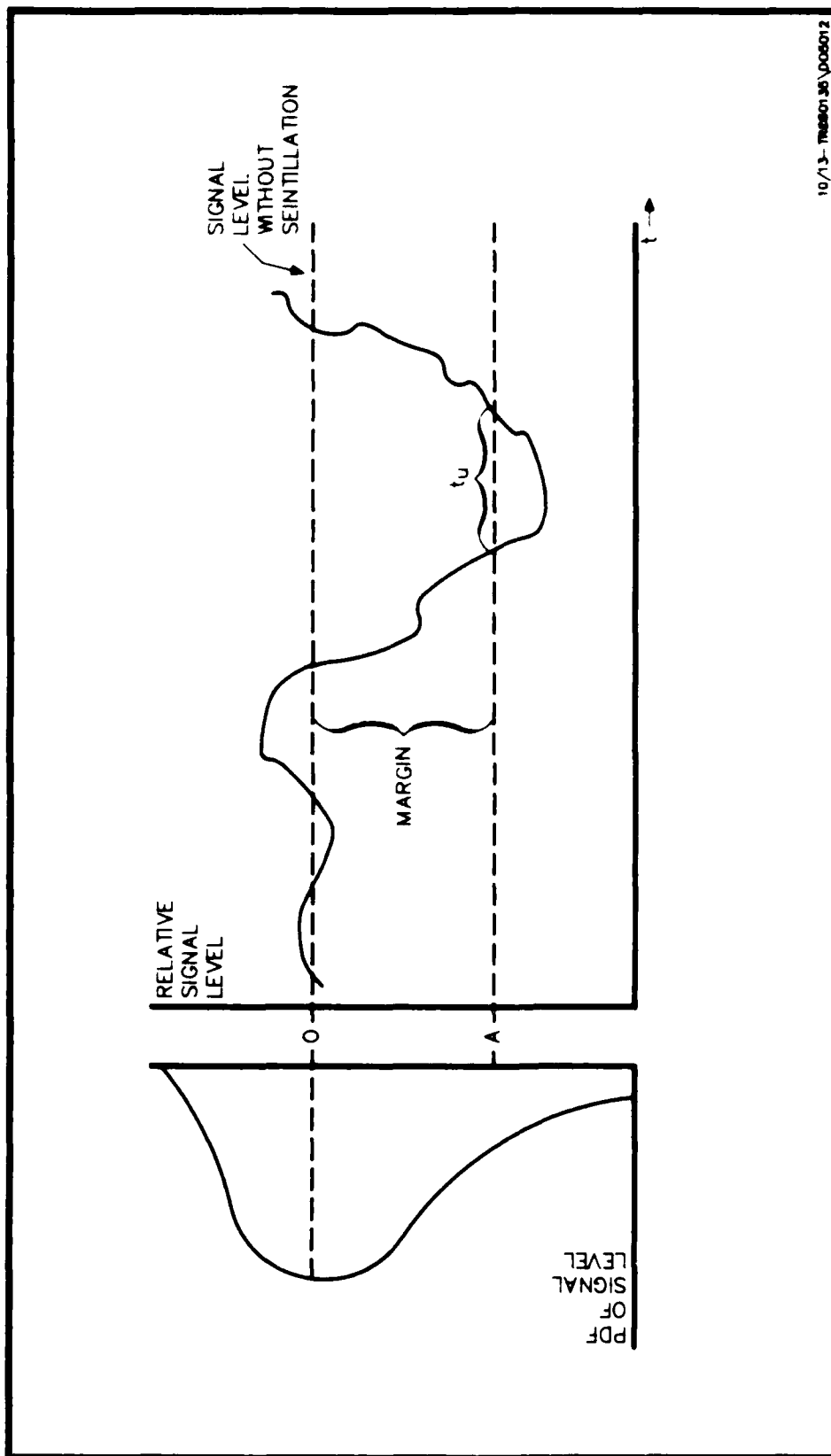
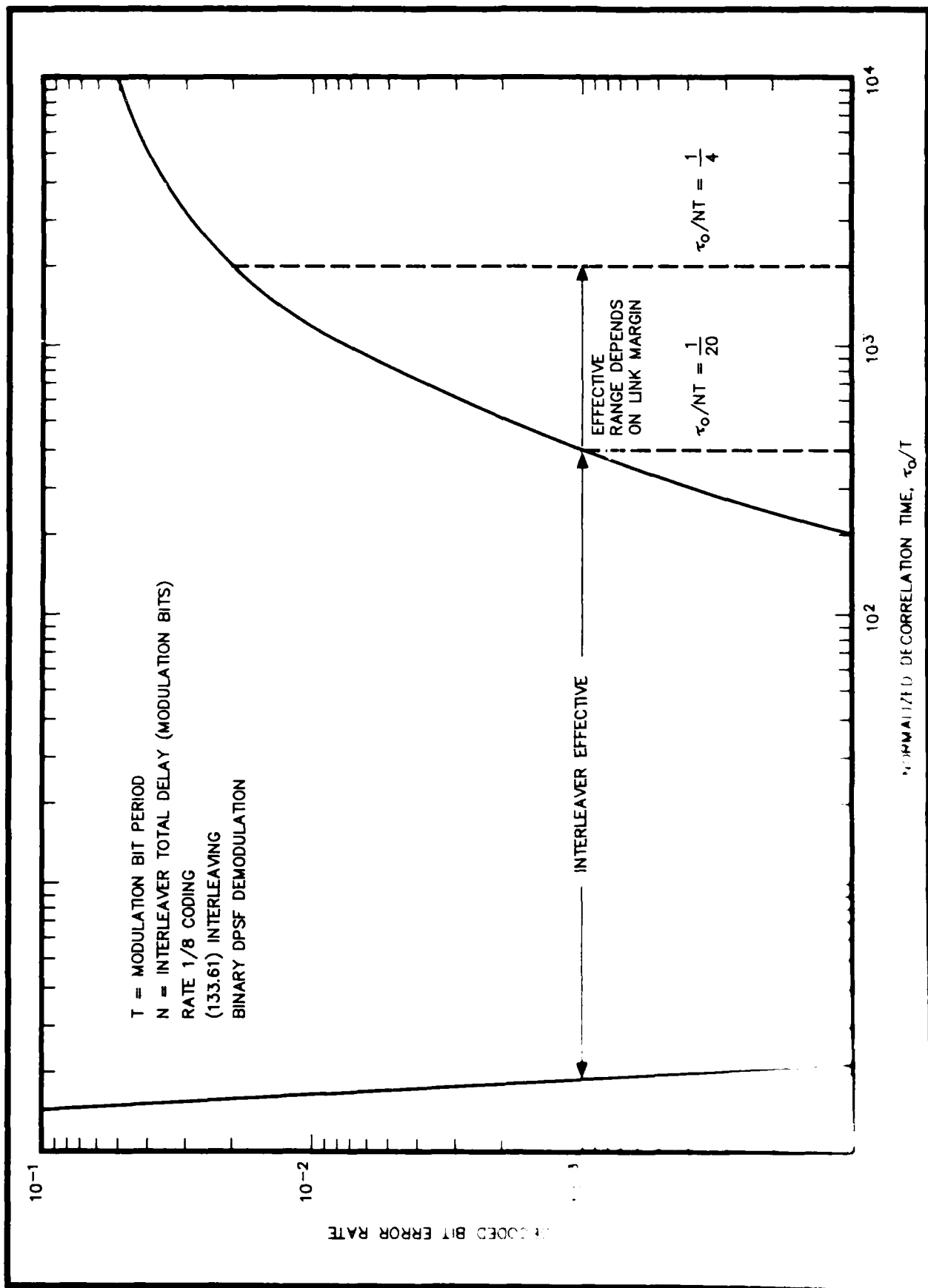


FIGURE 4.3-3: SAMPLE SIGNAL AND LINK UNAVAILABILITY TIME  $t_u$  ( $t_u > 10\tau_0$ )



On the other hand, if the user-defined interleaver is near-optimal or optimal, effective error randomization has been performed, and the bit error probabilities are exact, as opposed to lower bound approximations. In this case, if a coding option has been specified, the slow fade control distributor enables the appropriate coding module, and passes the optimally interleaved bit error probability as a parameter. Otherwise, the slow fade control distributor stores  $P_B$  in the execution database, and the executive control distributor becomes active.

If the user wishes to obtain a more precise measure of the bit error rate for sub-optimal interleaving, as opposed to the lower bound estimates for the bit error probability computed up to this point, a computer simulation is necessary. If the user is not interested in computing more precise bit error rates, the coding modules corresponding to the user-specified coding options will be enabled next with the lower bound bit error rate estimates. If no coding option has been specified, the resident  $P_B$  value is stored in the execution database by the slow fade control distributor, and the executive control distributor resumes active status.

When simulation is specified by the user, the executive control distributor becomes active and enables the computationally intensive fast fade simulator component TLCSC3. TLCSC3 operates in the same fashion as in the fast fade case, except the channel emulator will now generate a slow fade transfer function reflecting the slow fade parameter values. The bit error rate performance value would be a direct result of the sub-optimally interleaved information sequence.

It should be observed that although slow fade analysis may be accomplished by the fast fade simulator, at the expense of computation time, the reverse is not true. Communications in a fast fade environment can only be studied with the fast fade simulator because the rapidly changing physical conditions prohibit analysis, and generalizations of the channel (such as a Rayleigh distributed signal amplitude in slow fade) cannot be made.

Finally, if the user bypasses the interleaver module entirely, the coding modules that follow will default to the assumption that all error bits have been sufficiently randomized. That is, all bit error probabilities ( $P_B$ ) previously calculated represent precise measures, as opposed to lower bound approximations. In this case, the slow fade control distributor next would enable one of the coding modules, if the user has specified coding via the time diversity signal processing menu option.

#### 4.3.8 Unit 22 (Linear Block Coding)

Assuming that the interleaver has ideally randomized burst errors, the slow fade control distributor may enable one of two coding modules. The first module is the linear block code module, which, in turn, has three options available for the user to choose: binary block coding, Reed-Solomon (RS) cyclic coding, and concatenated coding. All three coding schemes improve system link performance by lowering the received bit error probability. The advantages and disadvantages of the various coding methods, as well as the definitions and storage locations of code parameters (such as  $(n,k)$ ,  $(N,K)$ ,  $E$ , etc.), are discussed in the Encoding/Decoding component of TLCSC2.

With  $(n,k)$  binary block codes, the decoded probability of error  $P_C$  is given as a direct function of  $P_B$ :

$$P_C = (1/n) \sum_{i=E+1}^n i \binom{n}{i} P_B^i (1-P_B)^{n-i}.$$

For  $(N,K)$  RS cyclic codes with alphabet size  $M = 2$  and any number of receivers ( $L$ ), the decoded probability of error is

$$P_C = (N+1)/2N \sum_{j=E+1}^N (j/N) \binom{N}{j} P_B^j (1-P_B)^{N-j}.$$

For (N,K) RS cyclic codes of alphabet size  $M > 2$  and  $L = 1$ , the decoded probability of error only will represent an upper bound approximation of the actual probability of error:

$$P_C < M^{-k(a-1)},$$

where  $k$  = block length,  
 $a = r_0/R_C$ ,  
 $R_C$  = code rate,  
 $r_0 = 1 - \log_2(1 - R_C E_b/N_0)$ ,

(N,K) RS cyclic codes with parameters  $M > 2$  and  $L > 1$  cannot be handled analytically and numerical simulation must be performed. In this case, the module will return control to the slow fade control distributor, which in turn will activate the executive control distributor. The executive control distributor will call the fast fade simulator component, which will compute the precise bit error rate. Refer to the paragraphs on sub-optimal interleaving in Unit 21 for a detailed description as to the rationale behind employing the fast fade simulator in this instance.

For concatenated codes, the combination of a binary inner code and a cyclic outer code is used<sup>1</sup>. The decoded probability of error is given by

$$P_C = [(N+1)/2N]P_{RS}.$$

<sup>1</sup> A convolutional code, such as the one described in Unit 24, may be used for the inner code. However, a numerical simulation then would be necessary for evaluating the link performance, as a result of the analytical complexity involved with convolutional coding. In this case, the module will return control to the slow fade control distributor, which in turn will activate the executive control distributor. The executive control distributor will call the fast fade simulator component, which will compute the precise bit error rate. Refer to the paragraphs on sub-optimal interleaving in Unit 22 for a detailed description as to the rationale behind employing the fast fade simulator in this instance.

$$P_{RS} = \sum_{j=E+1}^N (j/N) \binom{N}{j} P_W^j (1-P_W)^{N-j},$$

$$P_W = \sum_{i=E+1}^n \binom{n}{i} P_B^i (1-P_B)^{n-i}.$$

Once the decoded probability of error has been computed via one of the three linear block coding options, the slow fade control distributor will inform the executive control distributor to resume active status.

#### 4.3.9 Unit 23 (Convolutional Coding)

For the instances when the user has chosen linear convolutional coding, the slow fade control distributor will enable this module. (A description of convolutional coding is available under the Encoding/Decoding component of TLCSC3, as well as its advantages and disadvantages as compared with block coding.) In contrast to the more rigorous calculation of the symbol error rate obtained via simulation, the convolutional coding module provides the user with an approximate error probability upper bound

$$P_C < p(D).$$

$p(D)$  is a polynomial in  $D$  with integer coefficients, and  $D$  is computed from the nominal bit error probabilities ( $P_B$ ). The coefficients of  $p(D)$  are determined by the code rate ( $R_C$ ), constraint length ( $K$ ), and alphabet size ( $M$ ). Polynomial expressions for symbol error probabilities are shown below for some common  $[R_C, K, M, D]$  parameter sets.

- 1)  $[R_C=1/2, K=7, M=2, D=2 P_B(1-P_B)]:$

$$P_C < (1/2)(36D^{10} + 211D^{12} + 1404D^{14} + \dots)$$

- 2)  $[R_C=1/3, K=7, M=2, D=2 P_B(1-P_B)]:$

$$P_C < (1/2)(D^{14} + 20D^{16} + 53D^{18} + \dots)$$

- 3)  $[R_C=1/2, K=7, M=4 \text{ (orthogonal)}, D=2 P_B(1-P_B)/3 + 2P_B/3]:$

$$P_C < (1/2)(7D^7 + 39D^8 + 104D^9 + 352D^{10} + 1348D^{11} + \dots)$$

- 4)  $[R_C=1/3, K=7, M=8 \text{ (orthogonal)}, D=2 P_B(1-P_B)/3 + 2P_B/3]:$

$$P_C < (1/2)(D^7 + 4D^8 + 8D^9 + 49D^{10} + 92D^{11} + \dots)$$

- 5)  $[R_C=1/v, K=2k+1, M=2^k \text{ (orthogonal)},$

$$D=2 P_B(1-P_B)/(M-1) + (M-2)P_B/(M-1)]:$$

$$P_C < 2^{k-2}D^{2v}/(1 - vD^{v-1} - (2^k - 1 - v)D^v)^2$$

- 6)  $[R_C=1/v, K=2k+1, M=2^k \text{ (semi-orthogonal)},$

$$D=2 P_B(1-P_B)/(M-1) + (M-2)P_B/(M-1)]:$$

$$P_C < (1/2)D^K$$

If the user is not satisfied with the error probability upper bound approximations, more precise symbol error rates may be calculated by simulation. When simulation is specified, the slow fade control distributor enables the executive control distributor after storing the error probability bounds in the execution database. The executive control distributor subsequently will activate the fast fade simulator (TLCSC3) to compute the symbol error rate value. (Refer to the paragraphs on sub-optimal interleaving in Unit 21 for a detailed description as to the rationale behind employing the fast fade simulator in this instance.)

#### 4.4 TLCSC3 (FAST FADE SIMULATOR)

One of the two link evaluation components of the system design requirements tool is the fast fade simulator, represented by TLCSC3. This component is activated by the control distributor module based on computations within the mode selection control module.

When analytic relations under slow fading cannot be applied to the link evaluation process, numerical simulation methods are used to evaluate the link performance. These numerical methods take into account all components involved in a transmit-receive communications link, including the following: the information sequence generator; additive white Gaussian noise generator; signal modulator/demodulator; receiver equalizers; fading channel emulator; and diversity devices.

In addition, TLCSC3 includes a fast fade control distributor unit that monitors the operations of the above simulator components, much like the control distributor resident in the executive component. The execution modules fall under one of three categories (shown in Table 4.4-1): signal processing, channel emulation, and support. A functional diagram of the simulator is shown in Figure 4.4-1, followed by the flow chart of the modules in Figure 4.4-2.

##### 4.4.1 Unit 24 (Control Distributor)

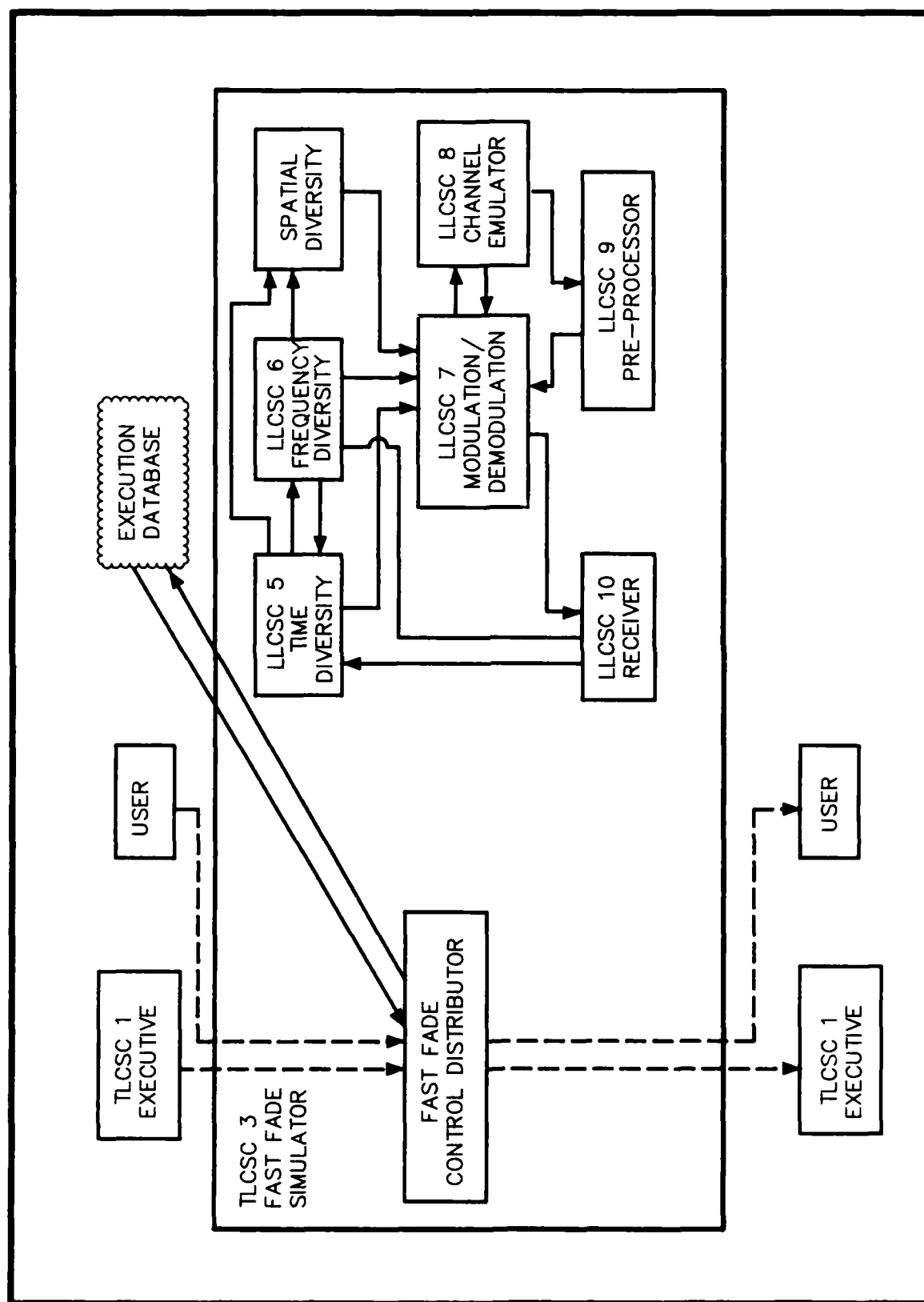
The fast fade control distributor module becomes active when the fast fade simulation component TLCSC2 is enabled by the system control component. This control distributor is responsible for displaying the options available to the user for signal and channel emulation, as well as enabling those user-specified execution modules for proper fast fade simulator operation.

The fast fade control distributor first displays the various signal processing options to the user through a menu. The menu will contain those components listed in column (a) of Table 4.4-1. Each component, when selected, will contain several levels of sub-menus, listing those components/parameters that

TABLE 4.4-1

## CATEGORIZATION OF FAST FADE SIMULATION COMPONENTS AND UNITS

(a) SIGNAL PROCESSING COMPONENTS/UNITS	(b) CHANNEL EMULATION UNITS	(c) SUPPORT UNITS
TIME DIVERSITY FREQUENCY DIV. SPATIAL DIV. MODULATION PREPROCESSOR RECEIVER	SPECTRAL ESTIMATE SCATTERING FUNCTION COEFFICIENT GENERATOR ADDITIVE NOISE GEN.	SIGNAL GENERATOR FFT BER



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FIGURE 4.4-1: TLCSC3 FUNCTIONAL DIAGRAM

The mode selection control module has just calculated the mode selection variable. This variable's value, in this instance, signifies that the fast fade simulator must be used to evaluate link performance.

The random sequence generator is called by the fast fade control distributor (FFCD) to generate the initial random information sequence. This sequence serves as the basis for the signal that will be transmitted over the link.

Did the user select any of the time diversity options from the signal processing menu?

The FFCD calls the block unit to perform this interleaving technique upon the information sequence.

Regardless of the interleaving technique chosen, the FFCD will regain active status.

The fast fade control distributor is called by the executive control distributor to monitor the fast fade simulation. The user will be presented with the multi-level signal processing menu, from which he may choose signal processing option(s).

The FFCD regains active status once the initial information sequence has been generated.

Did the user select the interleaving time diversity option?

What interleaving technique did the user select from the inner-level interleaving menu of the inner-level signal processing menu?

The FFCD calls the convolutional unit to perform this interleaving technique upon the information sequence.

Did the user select the coding time diversity option?

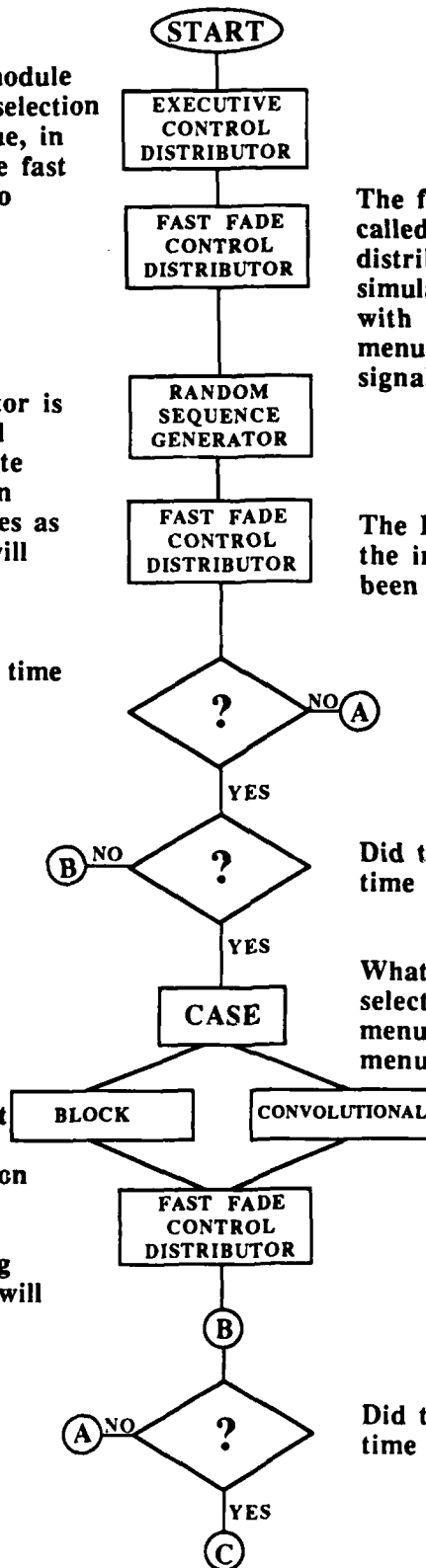


FIGURE 4.4-2: FAST FADE SIMULATOR

What encoding technique did the user select from the inner-level encoding menu of the outer-level signal processing menu?

The FFCD calls the binary block encoding unit to encode the information sequence via the binary block method.

The FFCD calls the cyclic encoding unit to encode the information sequence via the cyclic method.

The FFCD calls the concatenated encoding unit to encode the information sequence via the concatenated method.

The FFCD calls the convolutional encoding unit to encode the information sequence via the convolutional method.

The FFCD regains active status regardless of the encoding technique chosen.

Did the user select any of the frequency diversity options from the signal processing menu?

Which spread spectrum frequency diversity technique did the user select from the inner-level spread spectrum menu of the outer-level signal processing menu?

The FFCD calls the direct sequenced unit to perform direct sequenced spread spectrum processing on the information sequence.

The FFCD calls the frequency hopped unit to perform frequency hopped spread spectrum processing on the information sequence.

What frequency diversity technique did the user select from the frequency diversity subsection of the outer-level signal processing menu?

The FFCD calls the frequency selective unit to perform frequency selective frequency diversity processing on the information process.

The FFCD calls the multi-tone frequency selective unit to perform multi-tone frequency diversity processing on the information sequence.

FIGURE 4.4-2: FAST FADE SIMULATOR (Cont'd)

The FFCD regains active status regardless of the frequency diversity technique chosen.

The FFCD calls the spatial diversity unit to perform spatial diversity processing on the information sequence.

Does the environment in which the channel of the link is placed make the channel subject to flat fade conditions?

The FFT unit is enabled to transform the information sequence from the time domain to the frequency domain, so it can be easily combined with the filter. The combined result will be transformed back to the time domain.

The FFCD regains active status after all pre-filtering functions have been performed on the information sequence.

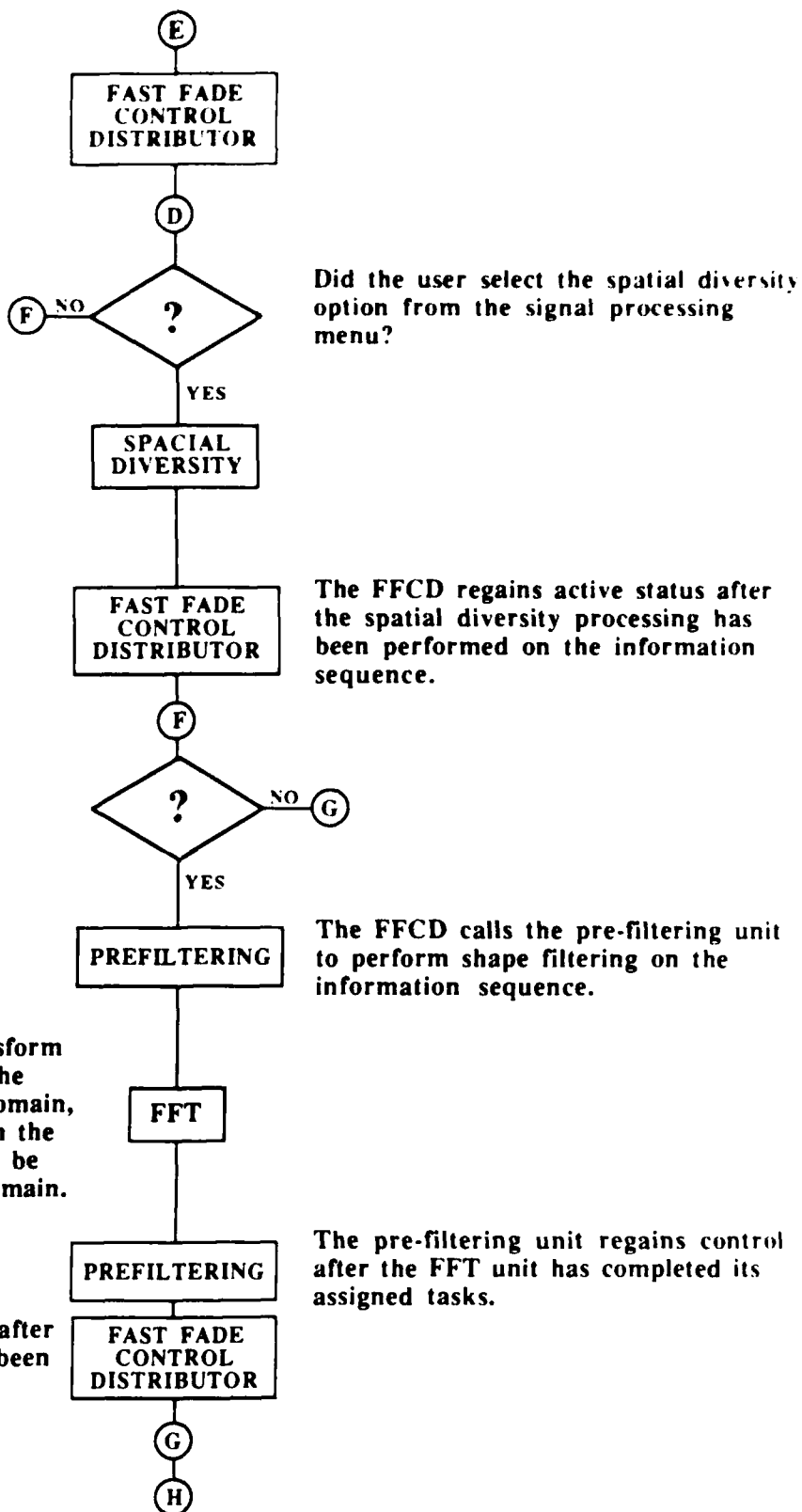


FIGURE 4.4-2: FAST FADE SIMULATOR (Cont'd)

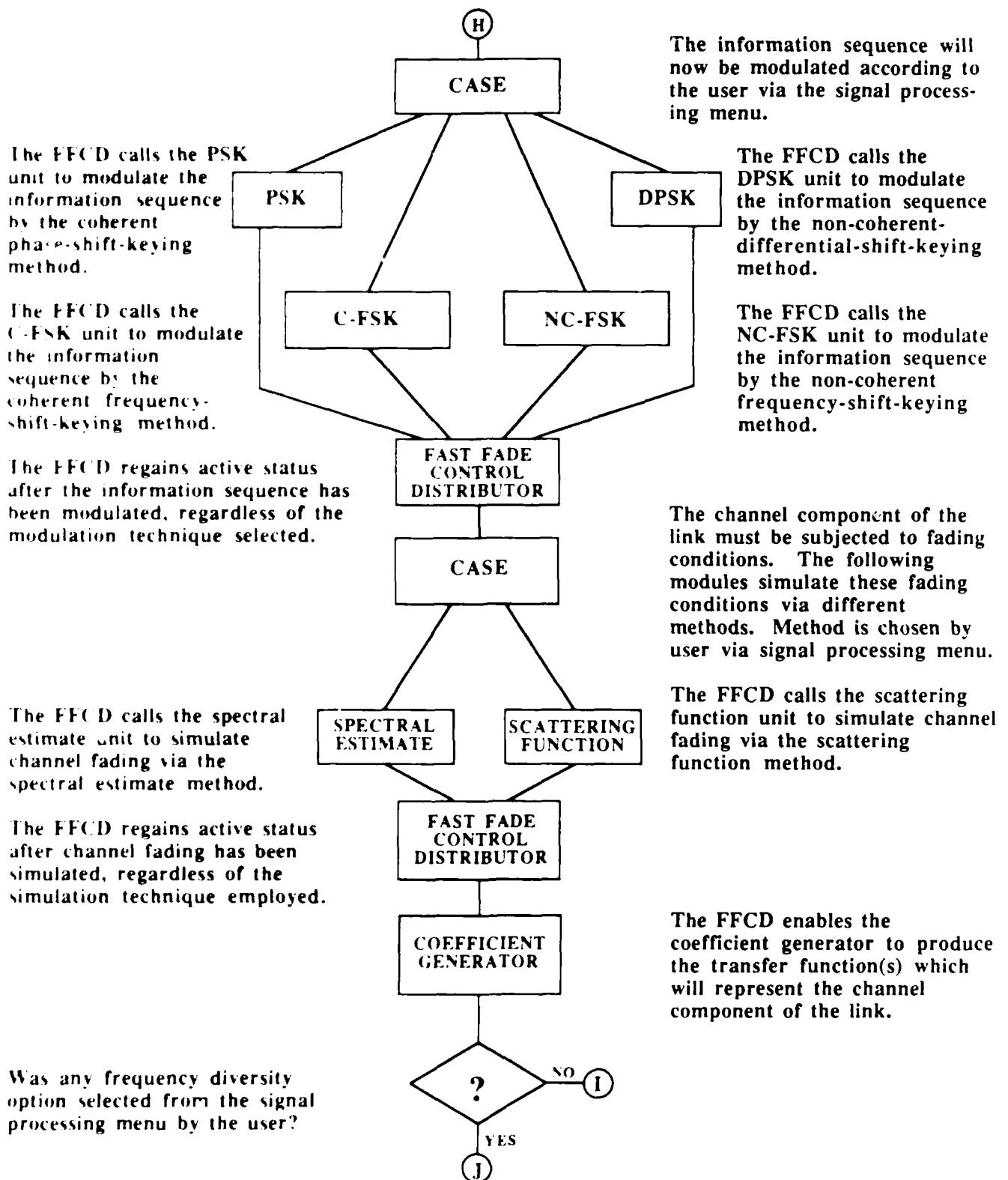


FIGURE 4.4-2 FAST FADE SIMULATOR (Cont'd)

Has the FFT unit been called  $BW_s/(\Delta f)c$  times (within this branch of the flow-chart)?  $BW_s/(\Delta f)c$  is the value calculated by the mode selection module that indicated fast fade simulation needed to be performed.

The coefficient generator regains control after the FFT unit executes.

The coefficient calls the FFT unit to transform channel coefficients related to frequency diversity to the time domain.

The coefficient generator resumes active status once the FFT unit has executed.

The FFT unit is called by the coefficient generator to transform the channel coefficients from the channel's top layer to the time domain.

Has the user, through the signal processing menu, specified a multi-layer channel?

Has the FFT unit been called for each of the lower layers of the channel? Each layer's channel coefficients must be transformed to the time domain.

The coefficient generator resumes active status once the FFT unit has executed.

The coefficient generator calls the FFT unit to transform a lower level's channel coefficients to the time domain.

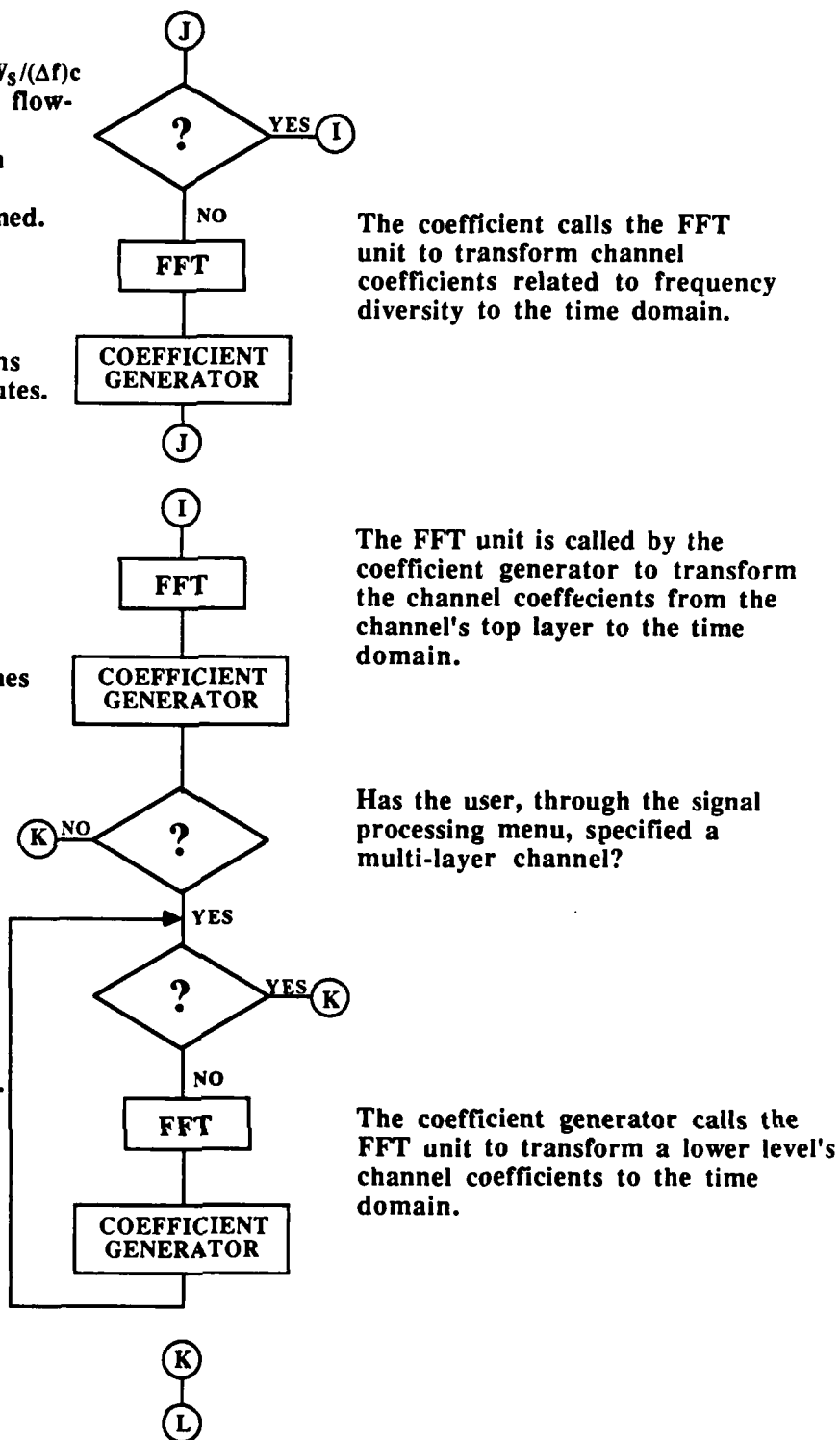


FIGURE 4.4-2: FAST FADE SIMULATOR (Cont'd)

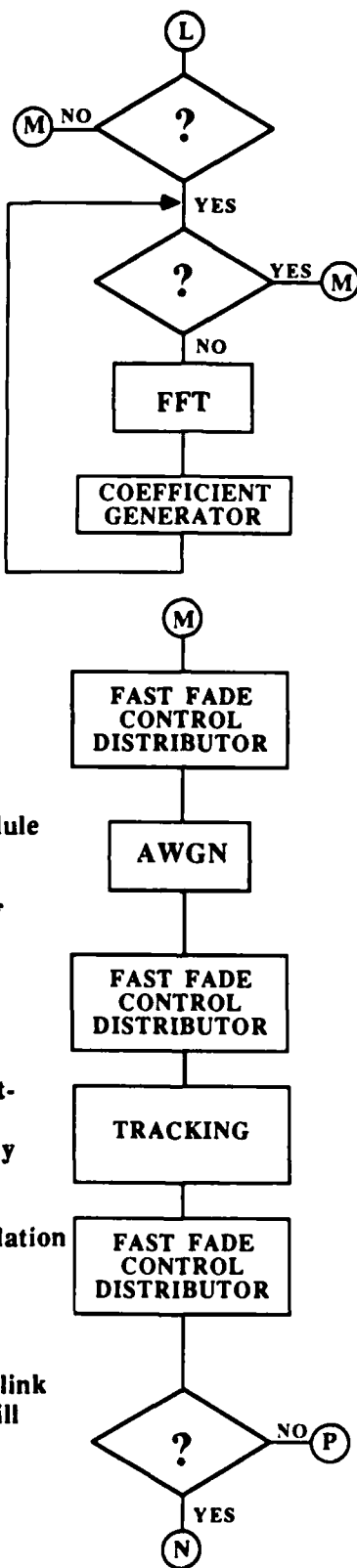
Has the FFT unit been called for each of the receivers in the receiver configuration? Each receiver must have its channel coefficients transformed to the time domain.

The coefficient generator resumes active status once the FFT unit has executed.

The FFCD calls the AWGN module to simulate the disruption of the modulated information signal. Disruption occurs in the form of additive white Gaussian noise.

The FFCD calls the tracking unit to perform automatic gain adjustments for normalization of the incoming signal levels, frequency tracking for synchronization of the incoming signal, and phase tracking when coherent demodulation will be used.

Is the channel component of the link placed in an environment that will subject the channel to flat fade conditions?



Did the user enable the spatial diversity option via the signal processing menu?

The coefficient generator calls the FFT unit to transform a receiver's channel coefficients to the time domain.

The FFCD regains active status after the channel transfer function(s) have been produced and all channel coefficients have been transformed to the time domain.

The FFCD regains active status after the simulation of the disruption of the modulated information signal via additive white Gaussian noise has been performed.

The FFCD regains active status after the tracking unit has completed all automatic gain and tracking operations.

FIGURE 4.4-2: FAST FADE SIMULATOR (Cont'd)

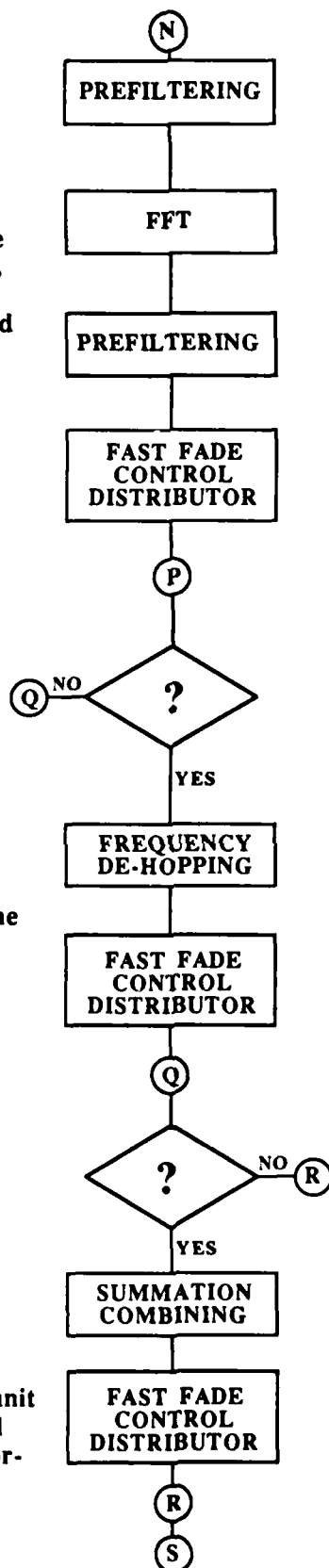
The FFT unit is called by the pre-filtering unit to transform the received signal from the time domain to the frequency domain, so it can easily be combined with the receiver filter. The combined result will be transformed back to the time domain.

The FFCD regains active status after all pre-filtering functions have been performed on the received information signal.

The FFCD calls the frequency de-hopping unit to despread the received information signal, based on the frequency hopped module that was used to spread the transmitted information signal.

Did the user select the spatial diversity option from the signal processing menu?

The FFCD regains active status after the summation combining unit has taken all received signals and combined them into a signal information signal.



The FFCD calls the pre-filtering unit to perform matched filtering on the received information signal. Matched filtering involves matching the receiver filter to the spectrum of the transmitted signal.

The pre-filtering unit regains control after the FFT module has completed its assigned tasks.

Did the user select the frequency hopped spread spectrum frequency diversity option from the inner-level spread spectrum menu of the outer-level signal processing menu?

The FFCD regains active status after the received information signal has been despread by the frequency de-hopping unit.

The FFCD calls the summation combining module to combine the signals received by each receiver. The combined signal subsequently will be demodulated.

FIGURE 4.4-2: FAST FADE SIMULATOR (Cont'd)

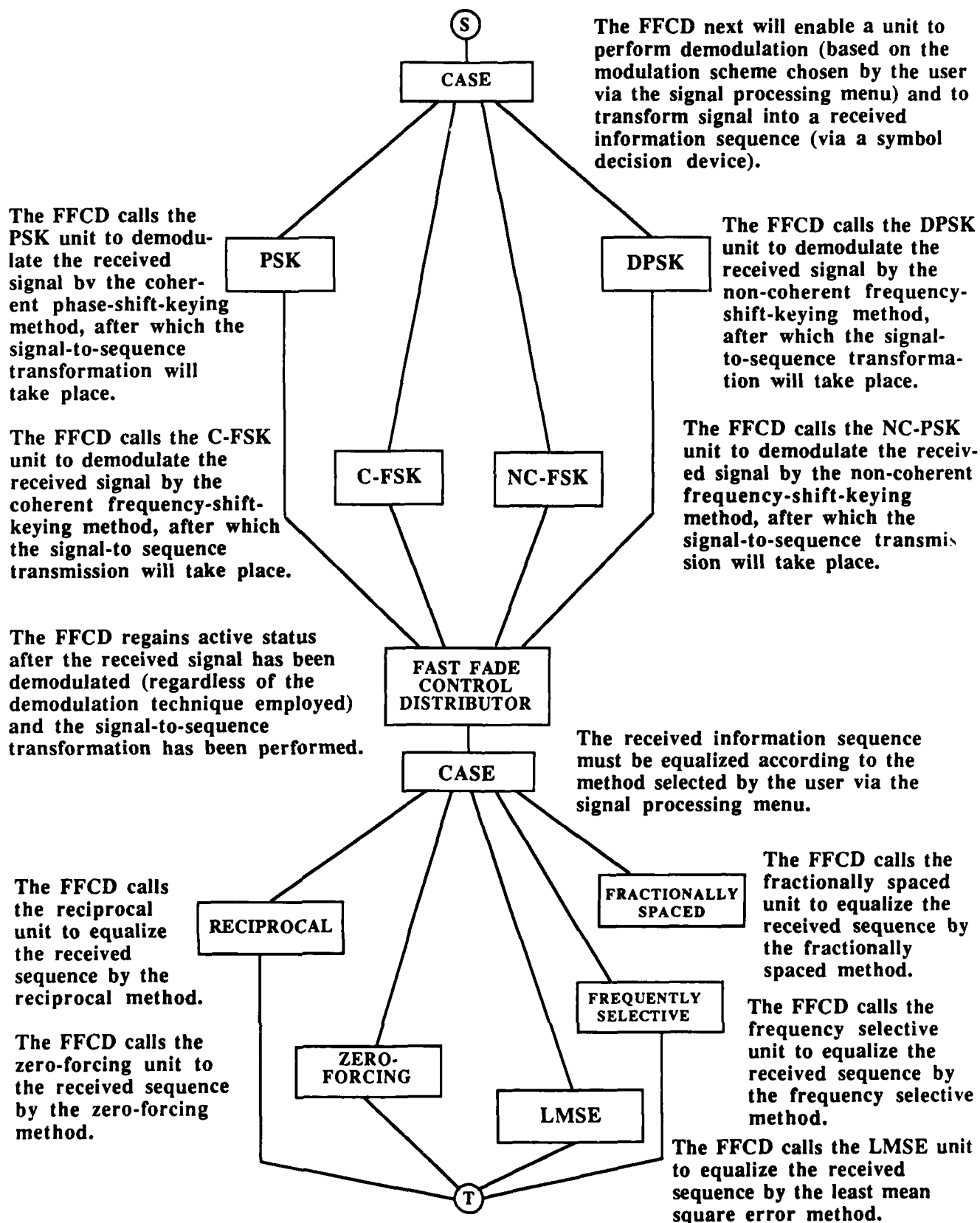


FIGURE 4.4-2: FAST FADE SIMULATOR (Cont'd)

The FFCD regains active status after the received sequence has been equalized, regardless of the equalization technique selected by the user.

The FFCD calls the chip combining unit to despread the direct sequence spread spectrum received information sequence.

Did the user select any of the time diversity options from the signal processing menu?

The FFCD next will enable a unit to perform decoding, based on the encoding scheme chosen by the user via the signal processing menu.

The FFCD calls the binary block decoding unit to decode the received sequence via the binary method.

The FFCD calls the cyclic decoding unit to decode the received sequence via the cyclic method.

Did the user select the direct sequenced spread spectrum frequency diversity option from the inner-level spread spectrum menu of the outer-level signal processing menu?

The FFCD regains active status after the chip combining unit has despread the direct sequence spread spectrum received sequence.

Did the user select the coding time diversity option?

The FFCD calls the concatenated decoding unit to decode the received sequence via the concatenated method.

The FFCD calls the convolutional decoding unit to decode the received sequence via the convolutional method.

The FFCD regains active status after the received sequence has been decoded, regardless of the decoding technique employed.

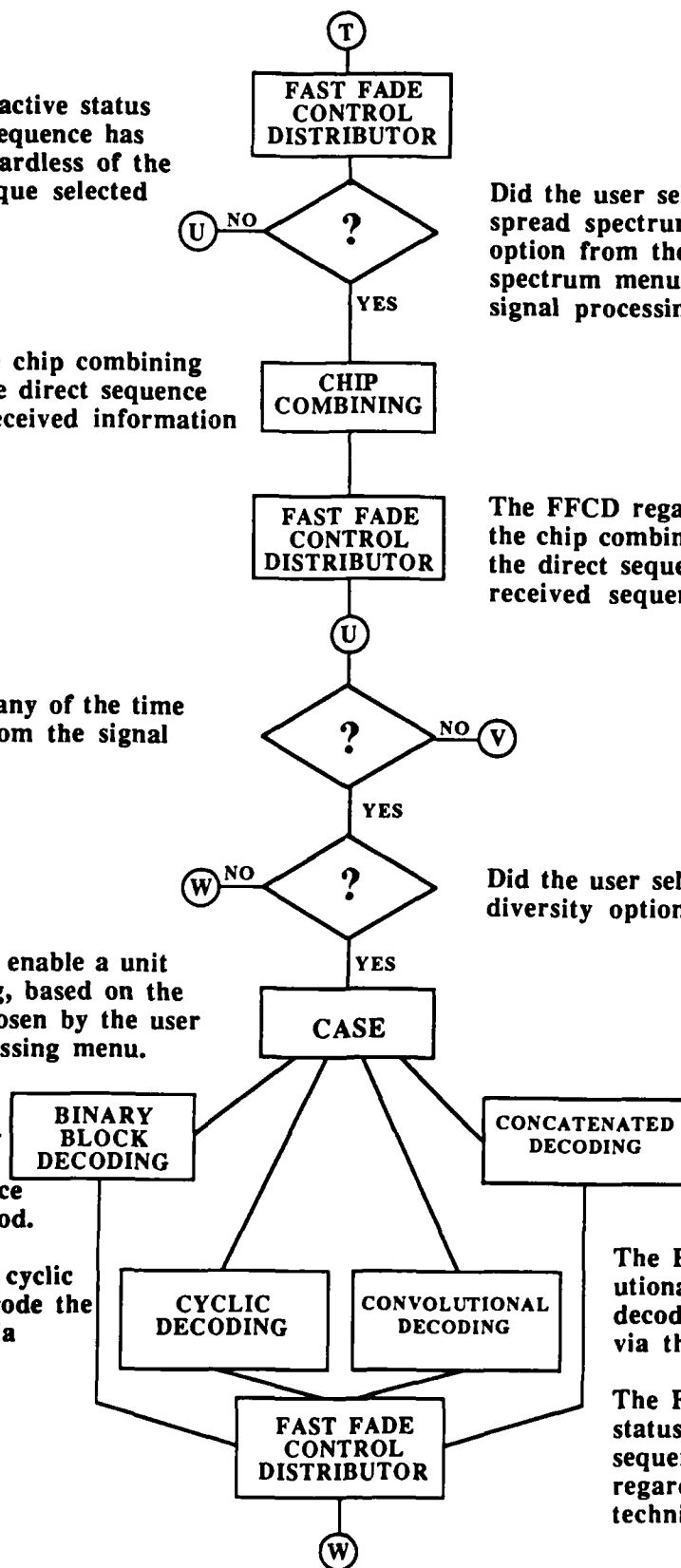


FIGURE 4.4-2: FAST FADE SIMULATOR (Cont'd)

Did the user select the interleaving time diversity option?

The FFCD calls the block unit to deinterleave the received sequence via the block deinterleaving method.

The FFCD calls the BER unit to compute the bit error rate for signal transmission. BER is computed by comparing the original information sequence with the received information sequence.

The executive control distributor regains active status after the bit error rate has been calculated. The executive control distributor next will enable the modules that will permit the user to see the results of the fast fade simulator's link performance evaluation.

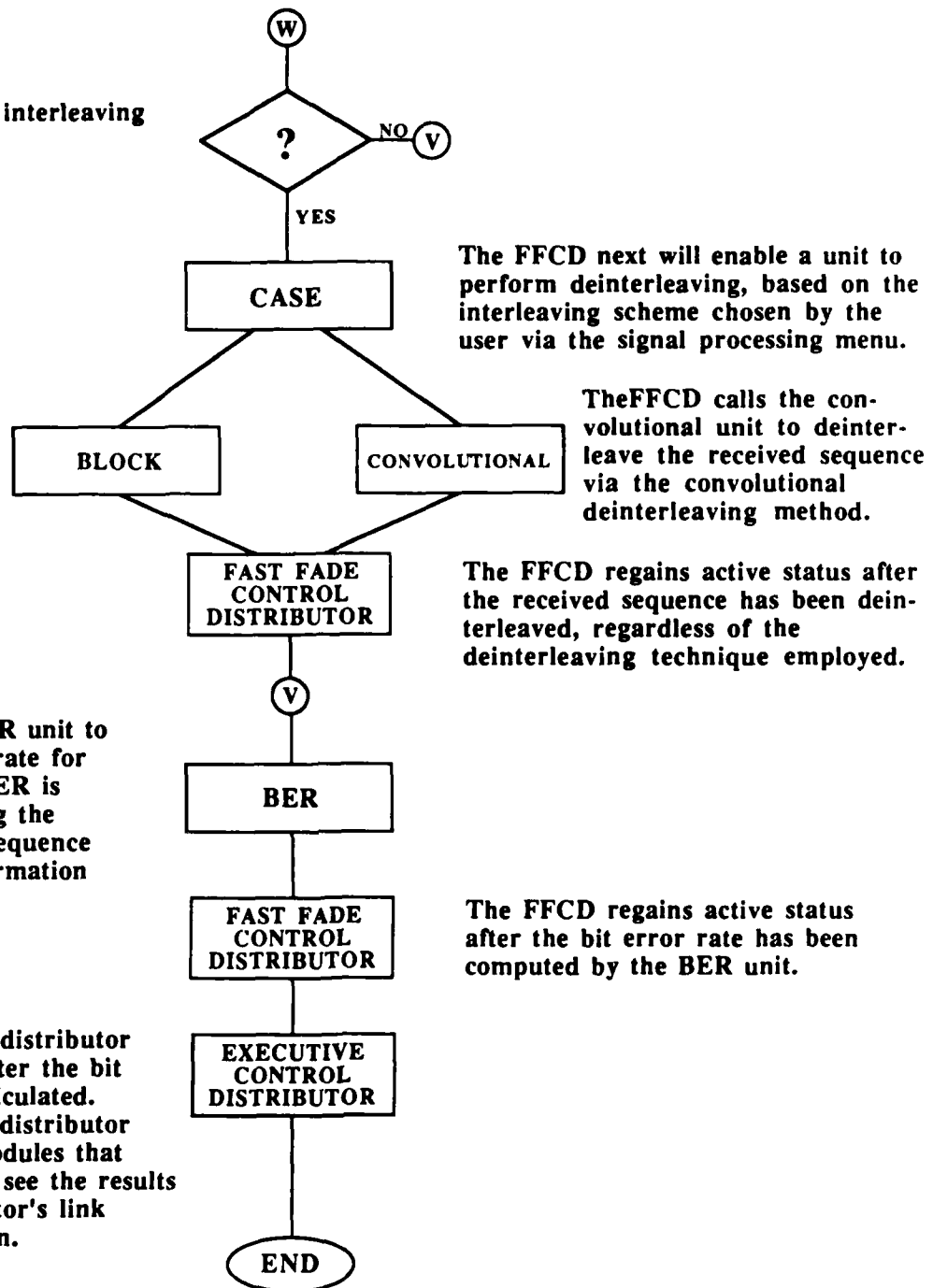


FIGURE 4.4-2: FAST FADE SIMULATOR (Cont'd)

may be assigned by the user for specifying the exact nature of the signal processing component. Parameters not assigned values by the user will be given default values from the execution database. However, if the user has specified a multi-link system without intermediate link processing, intermediate receiver parameter values will not be assigned at all; instead, other appropriate provisions are made to handle this case (see CSC5).

After specifying the signal options, the user may choose the fade simulation method, if conditions permit. If detailed low-level parameters had been input at the parameter input and revision phase of the tool's execution cycle, the fast fade control distributor would display the two options for fade simulation: the spectral estimate method or the scattering function method. However, if only high-level parameters had been specified, the fast fade control distributor automatically defaults to the spectral estimate fade emulator. The coefficient generator, as well as the additive white Gaussian noise generator, of the channel emulation component will be activated automatically after the chosen fade simulation component has finished executing.

The fast fade control distributor then selects those execution modules that correspond to the signal processing and channel emulation schemes chosen by the user from the menus, as well as enabling the support modules at the necessary times. The execution and support modules will carry out the processing on the original information bearing signal that was defined during the parameter input and revision phase of the tool's execution cycle.

The fast fade control distributor first activates the random sequence generator, which will emulate the information signal. After this task is completed, the diversity module(s) (time, frequency, spatial) are enabled in order to implement the user-specified signal processing scheme. The channel emulation modules (fade realization and additive noise) are activated next by the fast fade control distributor so that the processed information signal will encounter a simulated corruptive transmission. The next set of modules that are enabled by the control distributor implement the diversity combining,

decoding, despreading, etc., algorithms. The last module to be activated is the BER calculation module, which will provide a measure of the performance of the link being analyzed. After the BER has been determined, the system control component assumes active status.

#### 4.4.2 Unit 25 (Random Sequence Generator)

The first execution module enabled by the fast fade control distributor is the pseudorandom information sequence generator. This support module will create a binary sequence  $\{a_k\}_K$ , sampling from a prespecified density function for each  $a_n$ . The default density will be uniform over the alphabet size. The sequence will be of sufficient length to provide a statistically representative bit error rate (BER). After the generator completes this task, the fast fade control distributor will activate the signal processing component based on user input, resident in the execution database.

#### 4.4.3 LLCSC5 (Time Diversity)

The time diversity component is activated by the fast fade control distributor if the user has specified (via the execution database) that either coding or interleaving, or both, should be implemented in order to improve system performance. A coding operation performed by one of the coding modules before signal transmission will trigger the appropriate decoding operation to be performed by one of the decoding modules at the receiver. Because the processes of interleaving and deinterleaving are computationally identical, each of these tasks are implemented within the interleaving module.

The primary purpose of coding/decoding is to efficiently correct random errors that occur with some finite probability in transmission through any statistical channel. Interleaving/deinterleaving provides for the randomization of burst errors, such as those which may occur when transmitting a signal during a deep fade. These random errors then may be corrected by utilizing one of the coding methods found within the coding/decoding component.

As always, all relevant parameter values and constraints, as well as the random information sequence created by the random sequence generator, will be supplied by the execution database via the fast fade control distributor. The distributor also will monitor the storage and subsequent processing of the resulting coded/interleaved bit sequence. Following the consideration of all diversity options, including time diversity, the modulation component of LLCSC7 will be enabled by the distributor.

4.4.3.1 CSC2 (Interleaving/Deinterleaving). The interleaving/deinterleaving signal processing component is enabled by the fast fade control distributor to randomize burst errors caused by deep fades. The interleaving/deinterleaving module is therefore used only in conjunction with coding (described in component CSC3). The coding option, if selected by the user via the signal processing menu, will be implemented via the encoding/decoding component, activated immediately following execution of CSC2.

There are two general types of interleavers described by the parameter pair  $(n_2, n_1)$ : block interleavers and convolutional interleavers. For either case  $(n_2, n_1)$  indicates that no contiguous block of  $n_2$  symbols in the interleaved sequence contains more than one symbol from an  $n_1$  symbol length block in the original ordering. Therefore,  $n_1$  is related to the storage capacity of the interleaving simulator, and  $n_2$  is related to the average fade duration time of the channel below a specified signal level. Consequently,

$$n_2 = (R/R_C)I_L,$$

where  $R_C$  is the code rate,  $R$  is the data rate, and  $I_L$  is the interleave time (discussed below).

In addition to giving the user the opportunity to choose between the two interleavers, the interleave/deinterleave component first calculates the optimal interleave time ( $\hat{I}_L$ ).  $\hat{I}_L$  is calculated using parameters retrieved from the execution database, such as signal level ( $A$ ), average duration of fade ( $T_a$ ), unavailability time ( $U$ ), etc., via the relation

$$\hat{I}_L = B/R = 10T_a \ln[(1-\exp(-A^2/2))/U],$$

where  $T_a = \{\exp[A^2/E(A^2) - 1]/f_c(V/c) (2\pi A^2/E(A^2))^{1/2}\}$ ,  
 $B$  = number of bits interleaved,  
 $R$  = data rate,  
 $A$  = signal level,  
 $U$  = link unavailability probability,  
 $f_c$  = carrier frequency,  
 $V$  = relative velocity,  
 $c$  = speed of light.

This interleave time ( $\hat{I}_L$ ) is presented to the user, assisting him in determining the interleaver length to be used for the situation. The user will be offered the opportunity to use the optimal length if circumstances permit (such as sufficient storage space and delay times), or to use an interleaver length of his choice.

There do not exist distinct deinterleave modules, per se, since the processes of interleaving and deinterleaving are computationally identical but may use different parameters. For example,  $(n_2, n_1)$  block interleaving will result in the fast fade control distributor enabling the corresponding  $(n_1, n_2)$  block deinterleaver. Deinterleaving will be performed prior to decoding of the information sequence.

4.4.3.1.1 Unit 26 (Block Interleaving). The block interleaver implemented will be sufficiently described by the parameter pair  $(n_2, n_1)$ . The block interleaving function divides symbol sequences into blocks corresponding to a two-dimensional array,  $n_2$  rows by  $n_1$  columns, conceptually reading in symbols by rows and reading out symbols by columns, thereby providing the interleaved sequence. Deinterleaving of the information sequence would subsequently be performed at the receiver by reading in symbols by columns and reading out symbols by rows. An elementary example of the block interleaving/deinterleaving process is presented in Figure 4.4-3.

INFORMATION SEQUENCE :  $a_{11}a_{12}\dots a_{1L}a_{21}\dots a_{2L}\dots\dots a_{x1}\dots a_{xL}$

TRANSMITTED SEQUENCE :  $a_{11}a_{21}\dots a_{x1}a_{12}\dots a_{x2}\dots\dots a_{1L}\dots a_{xL}$

Suppose that, because of fading,  
 $\{a_{i2}\} \Rightarrow \{e\}$ , where  $e$  is the complement  
 of each  $a_{i2}$ . Then, the received sequence is

RECEIVED SEQUENCE :  $a_{11}a_{21}\dots a_{x1}e\dots\dots e\dots\dots a_{1L}\dots a_{xL}$

DEINTERLEAVED SEQUENCE :  $a_{11}e\dots\dots a_{1L}a_{21}e\dots a_{2L}\dots\dots a_{x1}e\dots a_{xL}$

With 8 bit words, for example,

$(a_{11}ea_{13}\dots a_{18}) \Rightarrow (a_{11}a_{12}a_{13}\dots a_{18})$ ,

corrected via some conventional code/decode  
 scheme.

FIGURE 4.4-3: BLOCK INTERLEAVING SCHEME

4.4.3.1.2 Unit 16 (Convolutional Interleaving). Another type of interleaver is the convolutional interleaver, illustrated in Figure 4.4-4. As can be seen, the convolutional interleaver is realized by the input sequence being multiplexed amongst a bank of shift registers, each of different, monotonically increasing lengths. The first input line to the interleaver incurs no delays; the second bank delays inputs  $(n_2/n_1)$  bits, etc.; and the last input line delaying by an amount  $(L-1)(n_2/n_1)$ . The input and output commutator switches move together in tandem from one register to the next. For the convolutional interleaver, then, an additional parameter  $(L)$ , besides  $n_1$  and  $n_2$ , is necessary to define the number of shift registers.

As with block interleaving/deinterleaving, the convolutional deinterleaver simply inverts the action of the convolutional interleaver. The convolutional interleaver/deinterleaver system is shown in Figure 4.4-5.

4.4.3.2 CSC3 (Encoding/Decoding). The encoding/decoding execution component is called upon by the fast fade control distributor at two junctures of the link performance evaluation process, provided that the coding was enabled via the time diversity option of the signal processing menu. The first activation of the encoding/decoding component takes place after the information sequence has been generated and possibly interleaved. At this time, the goal of the component is to encode the information sequence. The user will be presented with four encoding options (discussed below), from which he must select the one best suited to his application. The second activation of the encoding/decoding component occurs in the receiver, equalization. At this point, the component will decode the equalized signal, according to the decoding scheme that corresponds to the encoding scheme chosen.

There are four types of encoding schemes the user may choose to implement: block encoding, cyclic encoding, convolutional encoding, and concatenated encoding. Each encoding scheme has its advantages and disadvantages. Bit error rate performance is improved progressively from binary block to cyclic to concatenated (with binary block inner code) to convolutional to concatenated (with convolutional inner code) encoding schemes. However, each encoding scheme is more complex than its predecessor, and this complexity is compounded by the corresponding decoding scheme.

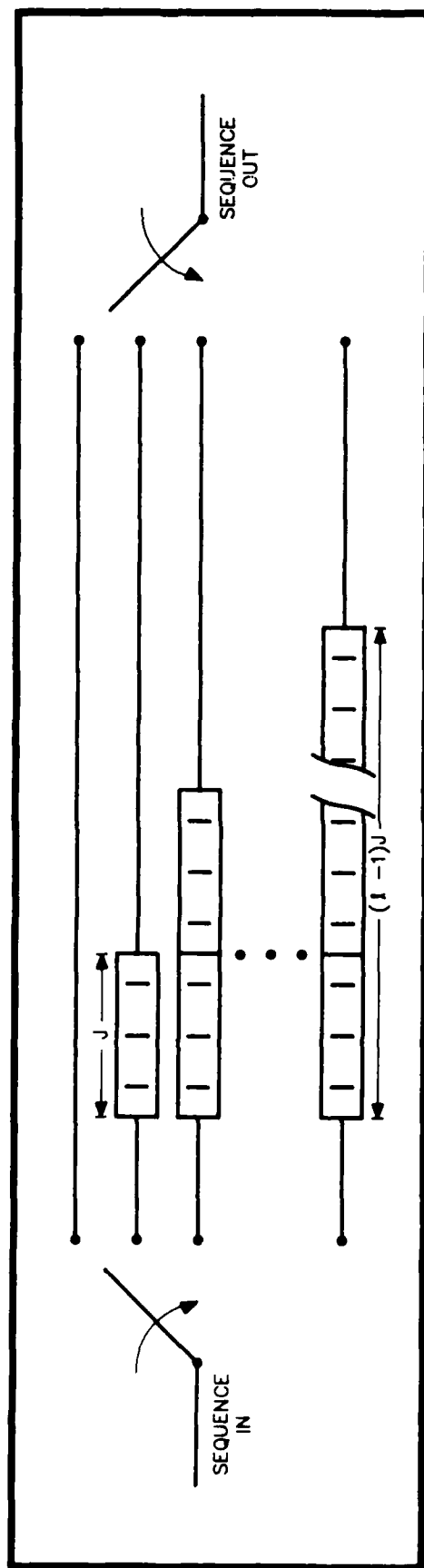
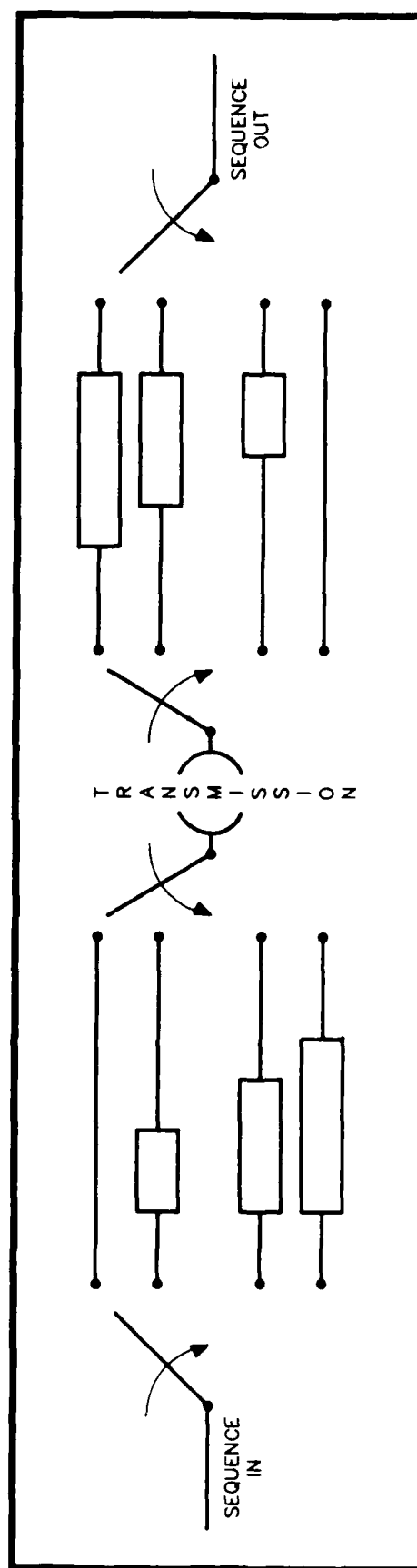


FIGURE 4.4--4: CONVOLUTIONAL INTERLEAVER



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FIGURE 4.4.-5: CONVOLUTIONAL INTERLEAVER/DEINTERLEAVER

4.4.3.2.1 Unit 17 (Binary Block Encoding). When this execution module is selected by the user, the parameter pair  $(n,k)$  is extracted from the execution database to enable the information sequence to be encoded. Here,  $n$  corresponds to the total number of bits per encoded word,  $k$  corresponds to the number of information bits per encoded word, and  $(n - k)$  corresponds to the number of error correction bits. The parameters  $(n,k)$ , along with the code type specification, such as Hamming, Golay, etc., precisely define the coding mechanism. More specifically, appropriate error correction bits are combined with the information bits in the specific code's characteristic manner to generate the encoded information sequence. A simple (7,4) Hamming code is illustrated in Figure 4.4-6.

4.4.3.2.2 Unit 29 (Binary Block Decoding). The binary block decoding execution module performs the inverse operation of the binary block encoding module. Parity check matrices (which are retrieved from the permanent database) are used with a table look-up to decode and correct the received encoded word/information sequence. The process of table look-up involves selecting the information word that corresponds to the encoded word, which has been removed of random errors by the parity check matrix. In the Hamming code example,  $(n,k)$  corresponds to a parity check matrix with  $n - k$  rows and  $n$  columns. Furthermore, because the minimum distance between code words is  $n - k$ , the error correction capability of the code is given as  $E = (n - k)/2$ . Therefore, received code words with more than  $E$  errors will be incorrectly decoded.

4.4.3.2.3 Unit 30 (Cyclic Encoding). When this execution module is activated by the fast fade control distributor, the parameter set  $(N,K)$  is retrieved from the execution database. This parameter set, where  $N$  denotes the length of the non-binary code word,  $K$  denotes the number of information symbols encoded, and  $(N - K)$  denotes the number of error correction symbols, along with the code type specification (for example, the Reed-Solomon (RS) code) sufficiently describes the coding mechanism. Furthermore,  $K/N$  defines the code rate; for every  $N$  input bits,  $K$  bits are outputted from an encoder that generates the error correction bits via a shift register feedback loop. The

## (7,4) HAMMING CODE EXAMPLE:

$$[H] = \begin{bmatrix} 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix} \quad \text{IS THE PARITY CHECK MATRIX.}$$

$[S] = [H][R] = [H][a_1 \ a_2 \ a_3 \ a_4 \ a_5 \ a_6 \ a_7]_t = [S_1 \ S_2 \ S_3]_t$  IS THE SYNDROME, DENOTING THE POSITION OF THE ERROR BIT.

$[R]$  IS A LEGAL RECEIVED CODE WORD IF  $[S] = [0]$ ; OTHERWISE,  $[T]$  IS THE DECODED WORD, WITH ERROR CORRECTION. FINALLY,  $[I]$  IS THE INFORMATION WORD, EXTRACTED FROM THE RECEIVED WORD VIA TABLE LOOK-UP.

INFORMATION WORDCODE WORD (LOOK-UP TABLE)

0 0 0 0	0 0 0 0 0 0 0
0 0 0 1	1 1 0 1 0 0 1
0 0 1 0	0 1 0 1 0 1 0
0 0 1 1	1 0 0 0 0 1 1
0 1 0 0	1 0 0 1 1 0 0
0 1 0 1	0 1 0 0 1 0 1
0 1 1 0	1 1 0 0 1 1 0
0 1 1 1	0 0 0 1 1 1 1
1 0 0 0	1 1 1 0 0 0 0
1 0 0 1	0 0 1 1 0 0 1
1 0 1 0	1 0 1 1 0 1 0
1 0 1 1	0 1 1 0 0 1 1
1 1 0 0	0 1 1 1 1 0 0
1 1 0 1	1 0 1 0 1 0 1
1 1 1 0	0 0 1 0 1 1 0
1 1 1 1	1 1 1 1 1 1 1

HENCE, IF  $[R]_t = [1 \ 1 \ 1 \ 1 \ 0 \ 0 \ 1]$ , THEN

$[S] = [0 \ 1 \ 1]_t$ , AND

$[T] = [1 \ 1 \ 0 \ 1 \ 0 \ 0 \ 1]$ , SO THAT

$[I] = [0 \ 0 \ 0 \ 1]$ .

FIGURE 4.4-6: BINARY BLOCK CODING (HAMMING)

error correction capability for cyclic codes is given by  $E = (N - K)/2$ . Cyclic codes also may be used as the outer code in a concatenated coding scheme. A schematic of a simple (7,4) cyclic encoder is shown in Figure 4.4-7.

4.4.3.2.4 Unit 31 (Cyclic Decoding). This execution module removes the cyclic code from the received information sequence. The cyclic decoder implementation is identical to that of the encoder, except for the error correction hardware, which may be realized by using  $(N - K)$  taps off the lower (encoder) register of length  $(N - K)$ . An upper register of length  $N$  is used to hold the received undecoded sequence. A diagram of the (7,4) cyclic decoder corresponding to the preceding section's cyclic encoder is shown in Figure 4.4-8.

4.3.3.2.5 Unit 32 (Convolutional Encoding). When the fast fade control distributor activates this execution module, the  $k$ ,  $n$ , and  $J$  parameters are retrieved from the execution database. The rate  $(k/n)$  and the constraint length  $(J)$  are used to encode the information sequence, and sufficiently describe the convolutional encoder. That is,  $n$  bits are outputted for every  $k$  bits into the encoder. Also, there are  $J$  stages, or shift registers, in the encoder realization. More specifically, appropriate modulo-2 addition operations are performed on the shift register contents to yield the convolutionally encoded output sequence. A diagram of the convolutional encoder appears in Figure 4.4-9 (general form) and in Figure 4.4-10 (length = 3, rate = 1/3).

4.3.3.2.6 Unit 33 (Convolutional Decoding). The optimum performance Viterbi decoder will be used to decode the convolutionally encoded information sequence after it has been accepted by the receiver. The Viterbi algorithm is a soft decision decoding process, incorporating knowledge of the decision costs for the preceding bits of the information sequence into the present bit decision analysis. Instead of making hard decisions for every bit received, the Viterbi decoder assigns costs to each probable path from the initialization symbol to a common termination time decision symbol/sequence. The decoder then chooses the lowest cost path after each termination cycle, resulting in the lowest cost path for the entire information sequence and, consequently, maximum likelihood decoding. The length of the termination cycle is determined by the path length at which all reasonable paths converge; however,

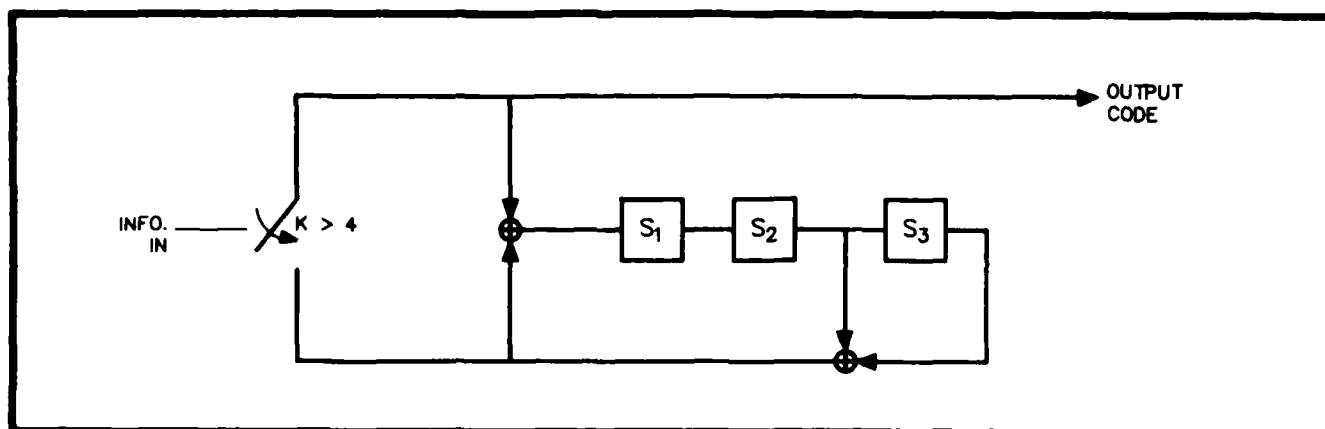
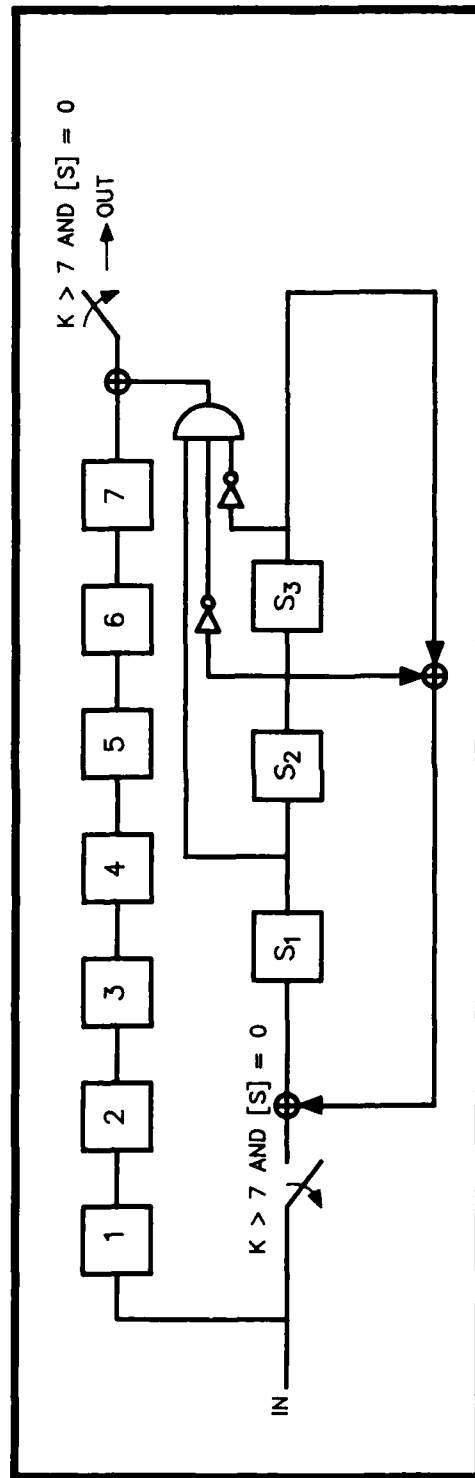


FIGURE 4.4-7A: (7,4) CYCLIC ENCODER

<u>INFORMATION WORD</u>	<u>CODE WORD</u>
0 0 0 0	0 0 0 0 0 0 0
0 0 0 1	0 0 0 1 0 1 1
0 0 1 0	0 0 1 0 1 1 0
0 0 1 1	0 0 1 1 1 0 1
0 1 0 0	0 1 0 0 1 1 1
0 1 0 1	0 1 0 1 1 0 0
0 1 1 0	0 1 1 0 0 0 1
0 1 1 1	0 1 1 1 0 1 0
1 0 0 0	1 0 0 0 1 0 1
1 0 0 1	1 0 0 1 1 1 0
1 0 1 0	1 0 1 0 0 1 1
1 0 1 1	1 0 1 1 0 0 0
1 1 0 0	1 1 0 0 0 1 0
1 1 0 1	1 1 0 1 0 0 1
1 1 1 0	1 1 1 0 1 0 0
1 1 1 1	1 1 1 1 1 1 1

IF  $[R] = [0\ 0\ 0\ 1\ 1\ 0\ 0]$ , THEN  $[T] = [0\ 1\ 0\ 1\ 1\ 0\ 0]$ .  
 HENCE,  $[I] = [0\ 1\ 0\ 1]$ .

FIGURE 4.4-7B: CODE WORDS FOR THE (7,4) CYCLIC CODE



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FIGURE 4.4-8: (7,4) CYCLIC DECODER

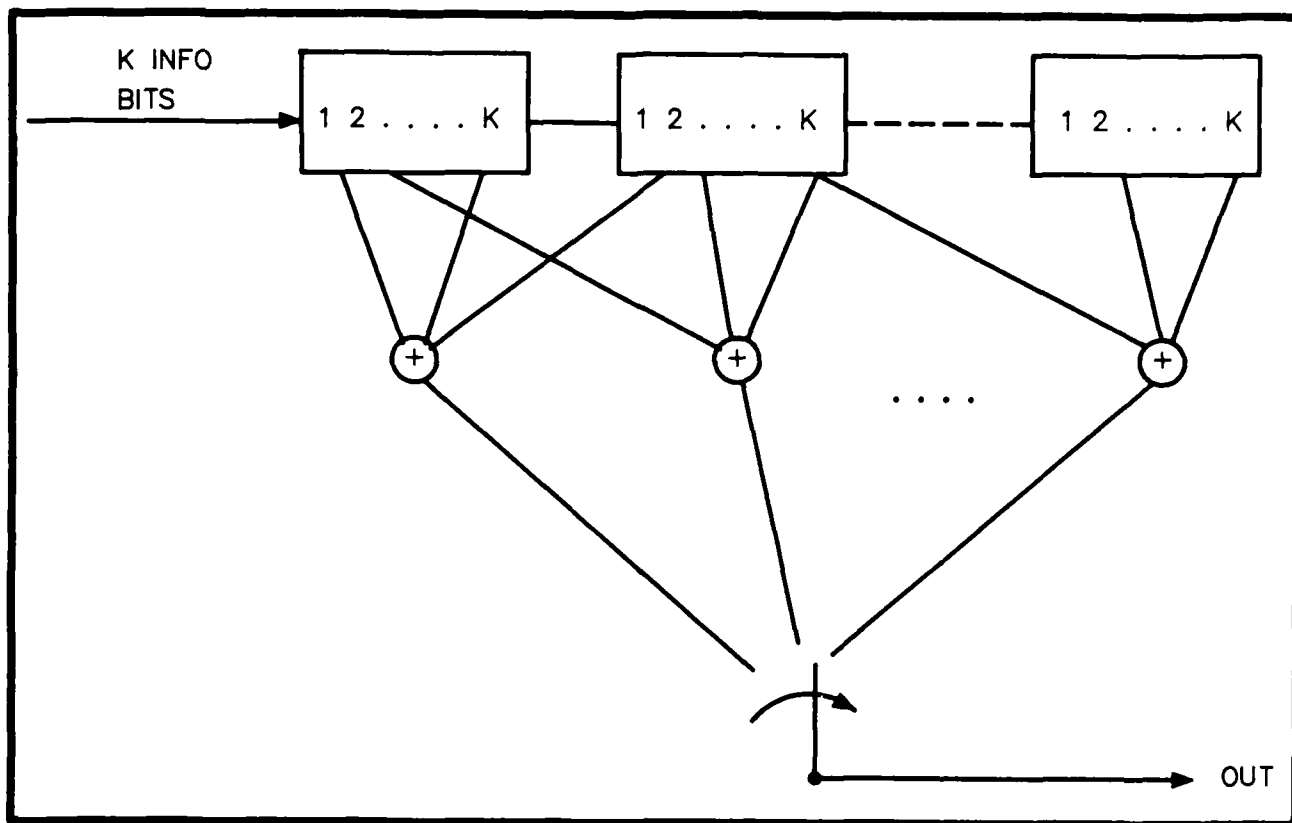


FIGURE 4.4-9: GENERAL CONVOLUTIONAL ENCODER

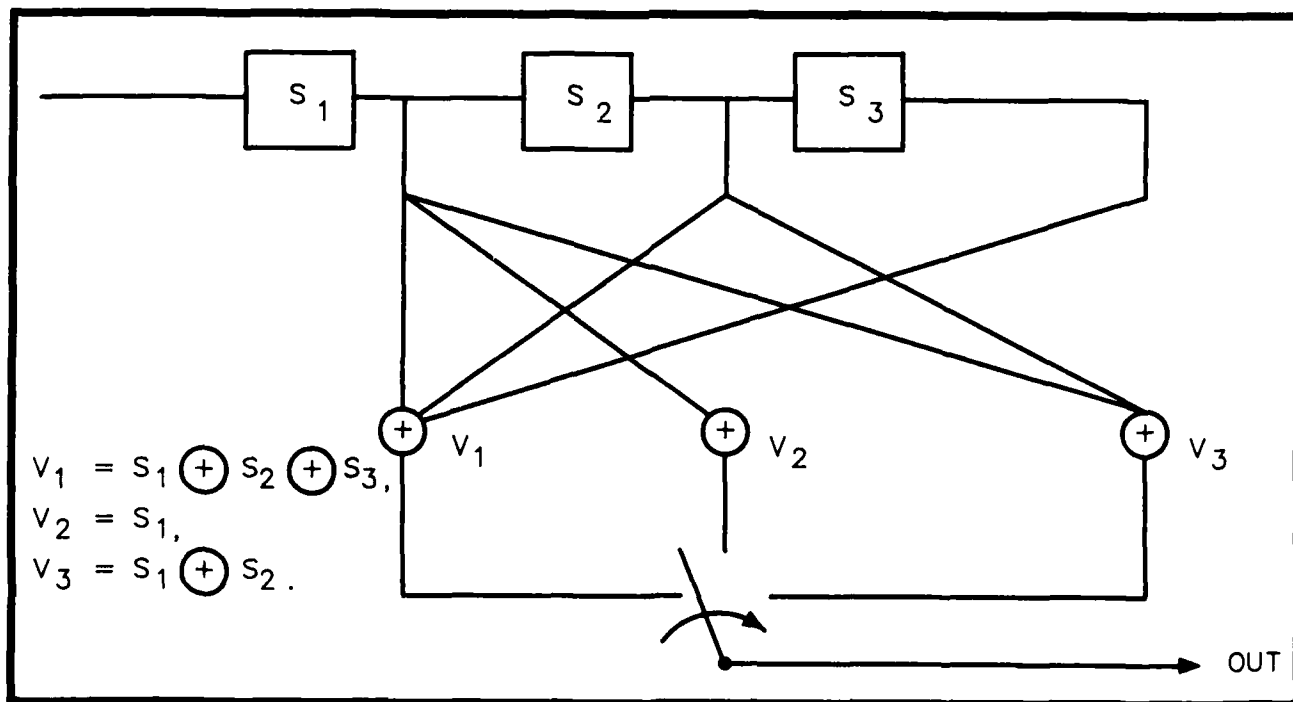


FIGURE 4.4-10: LENGTH 3, RATE 1/3 ENCODER

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if the state sequences are too large, the termination cycle is dependent on decoder device storage capacity, with longer cycles resulting in lower bit error rates. In the latter case, if paths have equal costs at the end of a termination cycle, any rational decision scheme for the symbol will suffice.

A formalization of the Viterbi algorithm to be used is as follows:

Variables:

$k$	discrete time index
$Y(x_k), 0 < x_k < M+1$	survivor path terminating at node $x_k$
$(x_k), 0 < x_k < M+1$	path length

Initialization Values:

$k = 0$   
 $Y(x_0) = x_0, Y(x_k)$  arbitrary  
 $(x_0) = 0$

Recursive Process:

$$(x_{k+1}, x_k) = (x_k) + h(x_{k+1}, x_k)$$

Find:

$(x_{k+1}) = \min(x_{k+1}, x_k)$ , smallest cost node transition for symbol at time  $k$

Store:

$(x_{k+1}), Y(x_k)$

## Decision:

Choose  $\min(x_{k+1})$  after each termination cycle time

$k = NK', N = 1, 2, \dots$

Change index  $k + 1 \Rightarrow k$ .

## Termination:

$k = K$ , where  $K$  is length of information sequence

## Result:

Minimum cost path  $(x_{k+1})$ , resulting in maximum likelihood sequence

Graphically, the decoding process is shown in Figure 4.4-11 and Figure 4.4-12.

**4.4.3.2.7 Unit 34 (Concatenated Encoding).** Two encoders are activated, in effect, when this signal processing module is enabled by the fast fade control distributor. That is, concatenated coding involves an inner code immediately followed by an outer code, combined to form a larger code. The inner code for this scheme is either a binary block code or a convolutional code; a cyclic code is used for the outer code. The binary block code or the convolutional code, when used as the inner code for the concatenated coding scheme, operate as described in UNIT28 and UNIT32, respectively. The cyclic code is generally used as the outer code for the concatenated coding scheme, operating as described in UNIT30. If the cyclic code is used as the outer code with an inner binary block code, their relationship is given by (using notations of UNIT28 and UNIT30):

$$N = q - 1 = 2^k - 1,$$

indicating that  $k$  information bits are mapped into one of  $q$  symbols. (It should be noted that an encoding scheme operates identically on a bit sequence -- raw data or precoded -- regardless of whether it is employed

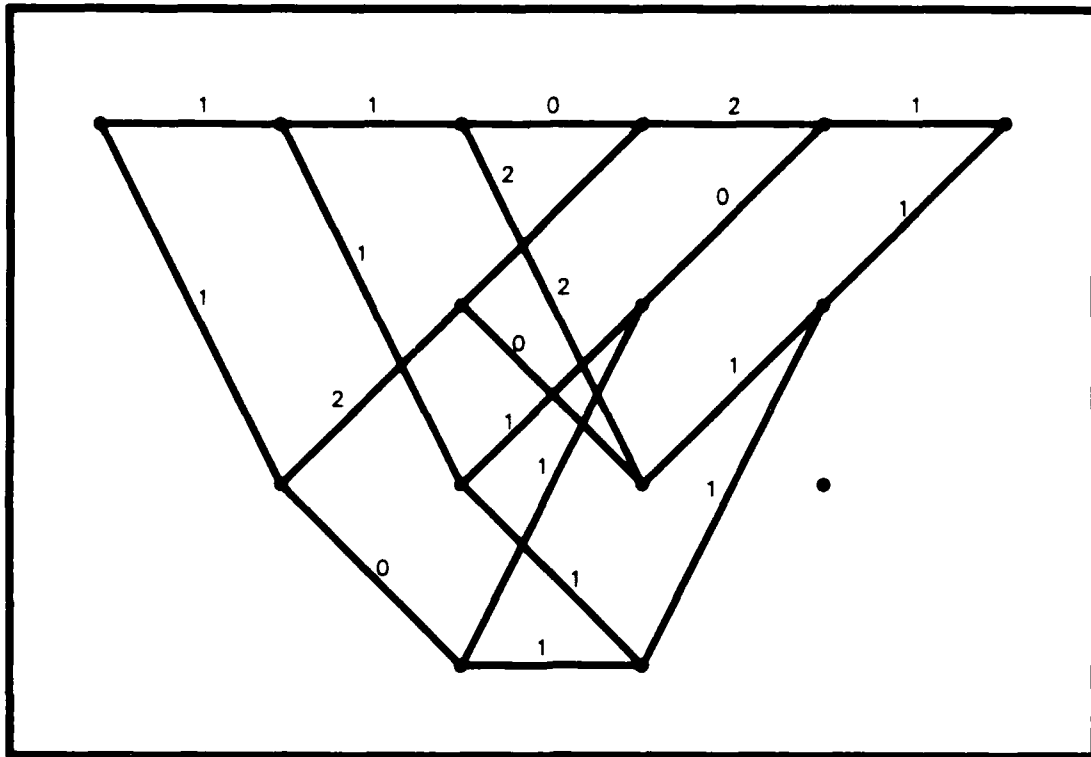


FIGURE 4.4-11: VITERBI ALGORITHM FOUR-STATE TRELLIS  
EXAMPLE, WITH TRANSITION METRICS

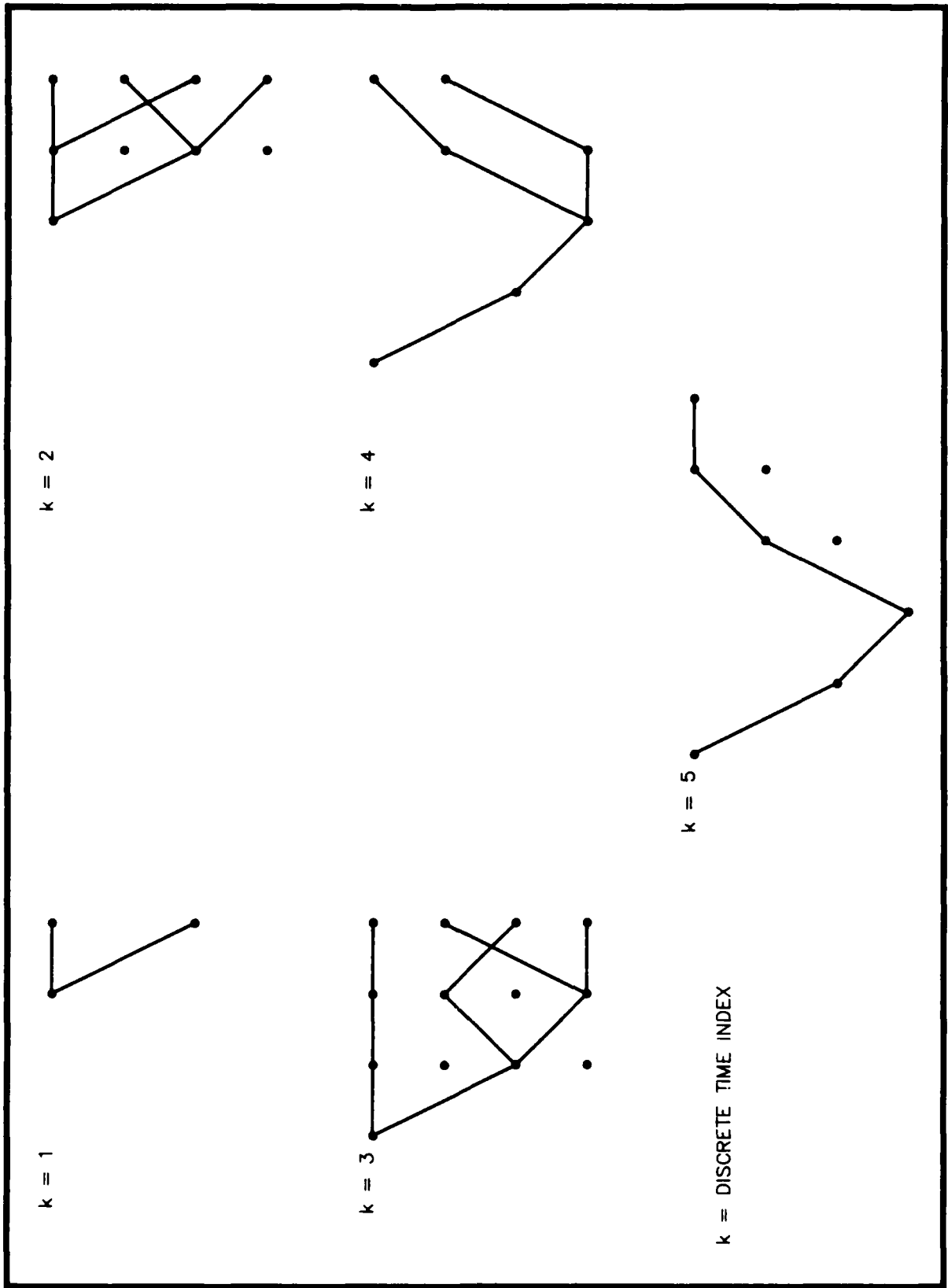


FIGURE 4.4-12: EVOLUTION THROUGH DECODER (EXAMPLE)

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independently or as part of the concatenated encoding scheme.) Hence, the actual implementation of the concatenated encoding is realized by the fast fade control distributor calling either the binary block encoder or the convolutional encoder, immediately followed by the cyclic encoding module.

4.4.3.2.8 Unit 35 (Concatenated Decoding). This execution module, when activated by the fast fade control distributor, first removes the outer cyclic code via Unit 32. The resulting partially decoded sequence then is sent to either the binary block or convolutional decoder (Unit 29 or Unit 33, respectively) for complete decoding. It should be noted that each of the individual decoding modules operate in the same fashion, regardless of the type of encoded sequence it receives. The result of this operation will be a restored information sequence.

#### 4.4.4 LLCSC6 (Frequency Diversity)

This signal processing component is activated by the fast fade control distributor if the user wishes to employ frequency diversity analysis for bit error rate performance improvement. All signal and channel parameters are retrieved from the execution database by this component. The fast fade control distributor will enable the modulation component of LLCSC7 after all diversity options have been considered.

Three methods of frequency diversity analysis are available: spread spectrum, multi-tone, and frequency selective signaling. The first two methods can be enabled directly by the user; however, the enabling of the third method is dependent on user specification, as well as the channel condition  $BW_s \gg (\Delta f)_c$ .  $BW_s$  denotes signal bandwidth, and  $(\Delta f)_c$  denotes channel coherence bandwidth.

4.4.4.1 CSC4 (Spread Spectrum). When channel fading is the only adverse effect encountered by a communications system, spread spectrum techniques cannot improve performance. Spread spectrum methods offer performance advantages for systems encountering hostile jammers (with fixed power).

Nevertheless, since it is not unreasonable that a system experiences both fading and jamming concurrently, the spread spectrum component is incorporated into MASCOT for completeness.

Jammer parameters entered by the user at initialization will be employed at the channel emulator/receiver components to simulate jamming effects on system performance with fading. Spread spectrum parameters (such as chip rate, hop rate, spread bandwidth, and modulation scheme) can be retrieved from the execution database and used to further process the information sequence, beyond coding and interleaving to combat jamming. Whether the direct sequence or frequency hopping option is chosen, the net effect of the spread spectrum signaling scheme is to increase the overall signal-to-noise ratio ( $E_b/N_0$ ) in the presence of an adverse jamming signal with fixed power. This increase in  $E_b/N_0$  is effected by increasing the available channel bandwidth, thereby decreasing the fixed power noise level while maintaining the same signal power, as shown below:

$$E_b/N_0 = (W/J)(S/R),$$

where      $S$  = received signal power,  
             $J$  = noise power,  
             $W$  = bandwidth,  
             $R$  = data rate.

The two spread spectrum methods differ in the demodulation technique employed at the receiver. If direct sequencing is used, the signal may be coherently demodulated. However, because of the rapid switching amongst the carrier frequencies, phase coherence is not maintained for a frequency hopped signal, and noncoherent demodulation must be used. The fast fade control distributor saves the chosen spread spectrum method so that the appropriate demodulation scheme will be enabled within the receiver component.

4.4.4.1.1 Unit 36 (Direct Sequenced Spread Spectrum). The direct sequence spread spectrum module multiplies each individual bit of the information bearing signal sequence by a pseudorandom binary sequence of chips which are generated by sampling from a uniform distribution. The chip sequence is saved

in the execution database and will be recalled later for chip combining at the receiver. (Unit 58 discusses chip combining in more detail.) The bandwidth of the signal is naturally increased because the product sequence has a pulse width equal to the chip pulse width, which is narrower in comparison to the original information bit pulse width. If, as a result of chip spreading, the  $BW_s \gg (\Delta f)_c$  condition is satisfied, the frequency selective modules of Units 18, 19, or 20 may be used for signal processing. Otherwise, flat fade processing is implemented.

4.4.4.1.2 Unit 37 (Frequency Hopped Spread Spectrum). This execution module allows the user to choose a set of frequencies (within center frequency separation guidelines and within the available channel bandwidth) for signal modulation. The accessing of each individual frequency is governed by a pseudorandom sequence generated by sampling from a uniform distribution. The effective available signal bandwidth has been increased by the use of randomly accessed multiple frequencies. Despreading is performed at the receiver, by referencing the pseudorandom frequency hop sequence created at the transmitter. (Unit 51 discusses frequency dehopping further.)

4.4.4.2 Unit 38 (Multi-Tone). The multi-tone frequency diversity scheme, activated by the fast fade control distributor, uses several modulation frequencies (assigned as for the frequency hopped case and retrieved from the execution database) which simultaneously transmit the information signal. (It should be noted that the available channel bandwidth  $W$ , specified by the user at the parameter input and revision phase, must satisfy  $W \gg (\Delta f)_c$ .) Each carrier frequency used must have a separation of at least  $(\Delta f)_c$  with respect to the center frequencies of all other carriers.

Different received signal-to-noise ratios, fade times, etc. are expected as a result of the different carrier frequencies. The multi-tone module informs the fast fade control distributor to subsequently enable the summation combining module, when the receiver component is activated, to output a new bit/symbol decision variable that is adjusted for the use of simultaneous multiple frequencies. (Unit 52 discusses summation combining further.) Link bit error rate performance should be improved with this multi-tone signaling scheme, as a result of an increase in signal-to-noise ratio.

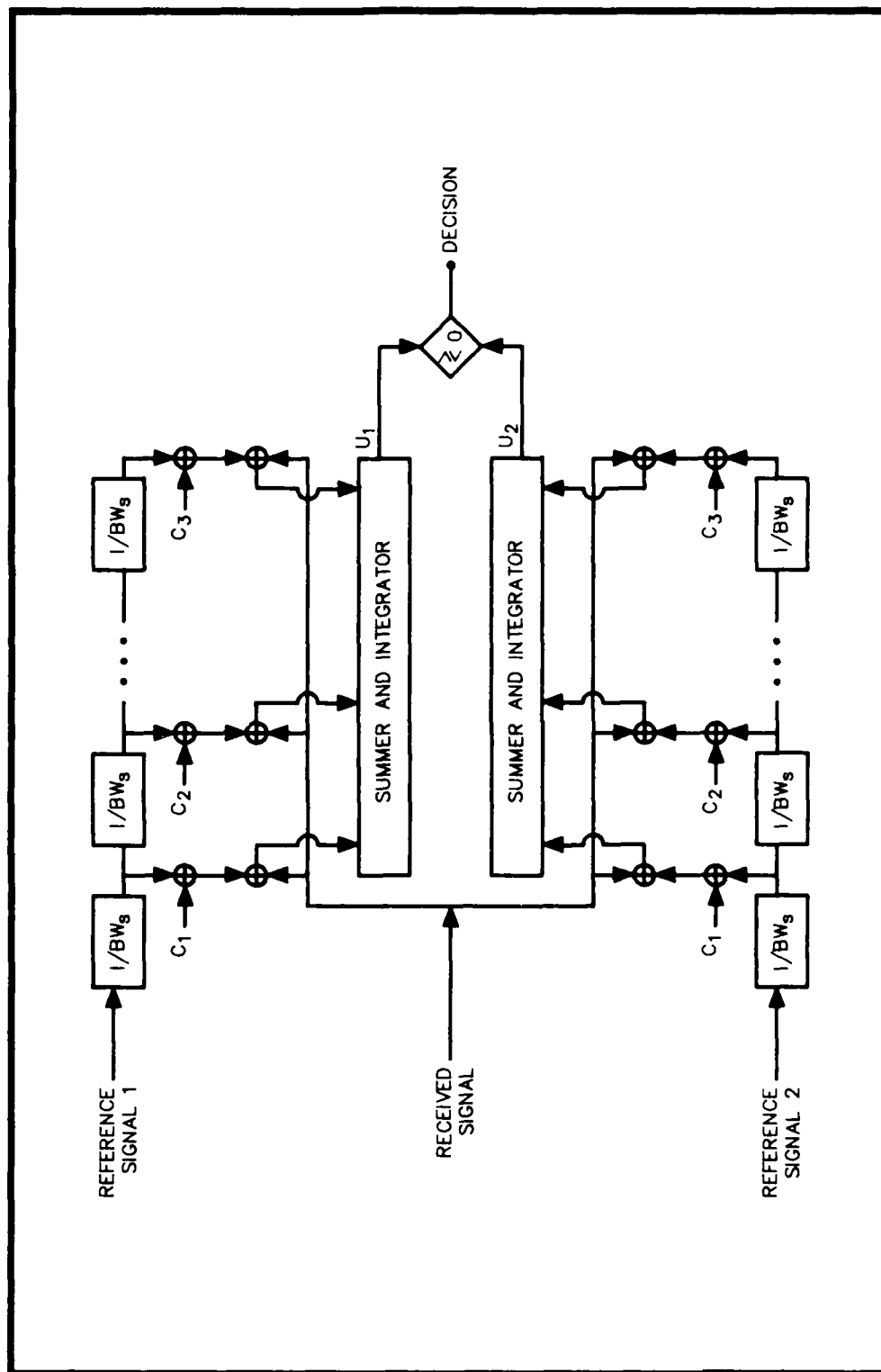
4.4.4.3 Unit 39 (Frequency Selective). When the user attempts to enable the frequency selective execution module, the fast fade control distributor ensures that the channel and wideband signal condition  $BW_S \gg (\Delta f)_C$  is valid. If the above condition is not valid, the user may choose another method of frequency diversity analysis, or alternatively, the user may choose not to consider any frequency diversity.

As opposed to the other frequency diversity schemes, frequency selective signaling is implemented entirely at the receiver. More specifically, a tapped delay line receiver, with approximately  $BW_S/(\Delta f)_C$  taps spaced  $T = 1/BW_S$  apart, is used to receive the wideband signal, resolving the independent multipath components for diversity reception. Reference signals created at the transmitter are retrieved from the execution database and multiplied at each tap by a weighting tap coefficient. The tap coefficients are least mean square error (LMSE) estimates of the time varying channel impulse response. The products (which should now resemble the actual channel-distorted signal) of each reference signal and the tap weights are used to multiply the incoming signal to implement a correlator receiver. These latter products are processed to determine the transmitted information data sequence.

The primary task of the frequency selective module, then, is to describe to the fast fade control distributor the type of receiver necessary, and to calculate the number of taps required for the tapped delay line. The tapped-delay line receiver for the frequency selective case is shown in Figure 4.4-13.

#### 4.4.5 Unit 40 (Spatial Diversity)

The fast fade control distributor activates this execution module, if the user wishes to use spatial diversity. Spatial diversity improves link performance, as with the multi-tone method, by using summation combining of the received signals, effectively resulting in an increased signal-to-noise ratio. In order to simulate spatial diversity, the parameter  $L$ , specifying the number of receivers, is retrieved from the execution database. The module then informs the distributor to direct the channel emulator to produce  $L$  independent sets of the channel transfer functions. These  $L$  sets of transfer functions will be



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FIGURE 4.4-13: TAPPED DELAY LINE FOR FREQUENCY SELECTIVE CHANNELS (BINARY SIGNALLING)

used to simulate the simultaneous use of L "parallel" receivers, each of which will provide the diversity summation combiner with an independent information sequence. Hence, the implicit assumption that the propagation paths are physically independent is made with the use of this module. The fast fade control distributor regains active status upon the completion of this task and enables the modulation component of LLCSC7.

#### 4.4.6 LLCSC6 (Modulation/Demodulation)

The modulation/demodulation component is activated by the fast fade control distributor at two distinct times in the link performance evaluation simulation. The component first is enabled after one or more of the diversity options have been applied to the information sequence. The user will be responsible for choosing a modulation scheme from the four options (enumerated below) presented to him. Each of the options simulates the process of modulating the information sequence. The component is enabled again after the preprocessor acknowledges proper reception of the information signal. At this point the received signal will be demodulated via the method corresponding to the option the user previously selected for modulation.

Modulation/demodulation makes use of the available channel bandwidth at higher frequencies than baseband for increased channel capacity and performance. Modulation is implemented before channel emulation, then, by multiplying the baseband signal by user selected carrier tones, or frequencies, which shift the baseband signal spectrum up to the carrier frequencies. The corresponding demodulation, coherent or noncoherent takes place after channel emulation, immediately following the received signal preprocessor. The modulation/demodulation schemes available are coherent M-ary PSK and FSK, and noncoherent M-ary FSK and DPSK. Each modulation scheme offers its own distinct set of advantages.

If coherent demodulation is possible, PSK is the recommended modulation scheme; the bit error probability performance for PSK modulation is significantly superior to that of the other modulation methods. NC-FSK provides the advantage of less hardware complexity than PSK since it may be

noncoherently demodulated. C-FSK offers bit error probability performance improvement with respect to NC-FSK, but it does not possess the latter's realization simplicity. Finally, DPSK offers the attractive features of both PSK and NC-FSK. That is, it may be noncoherently demodulated and still exhibit good bit error probability performance, at the expense of a small increase in complexity.

Coherent demodulation at the receiver is realized with local oscillators, replicating the frequency and phase of the transmitted carrier. Therefore, phase and frequency tracking hardware are required. The receiver/demodulator's ability to track is dependent on the tracker loop bandwidth and signal data rate. Noncoherent demodulation uses a less complex envelope detector, instead of the oscillator, to demodulate the signal, making phase coherence (and hence, phase tracking) unnecessary.

The advantages of M-ary signaling, as opposed to binary signaling, vary with the type of modulation used. With FSK, the end result is improved bit error probability performance at the cost of increased bandwidth. With PSK and DPSK, the reverse is true: M-ary signaling decreases the bandwidth necessary, but the bit probability of error increases.

4.4.6.1 Unit 41 (Phase Shift Keying). M-ary phase shift keying (PSK) entails switching the phase of the modulation carrier amongst M different values, equally spaced on the interval  $2\pi$ . Each of the M levels of the digital signal is mapped to a distinct phase  $\theta_m$  value.

$$S_m(t) = A \cos(2\pi f_c t + \theta_m), \quad 1 \leq m \leq M,$$

represents the transmitted signal. PSK is coherently demodulated, as shown in Figure 4.4-14.

4.4.6.2 Unit 42 (Frequency Shift Keying). M-ary frequency shift keying (FSK) is realized by switching the carrier waveform frequency ( $f_c$ ) amongst M constant frequencies,

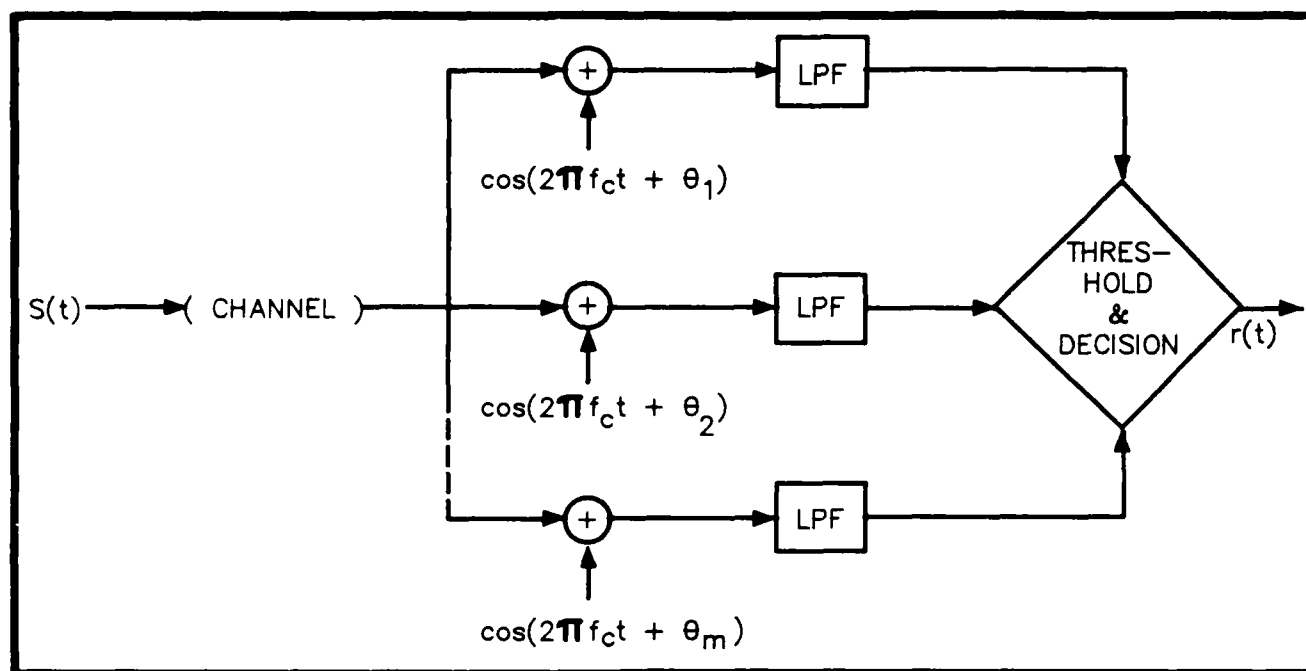


FIGURE 4.4-14: M-ARY PSK

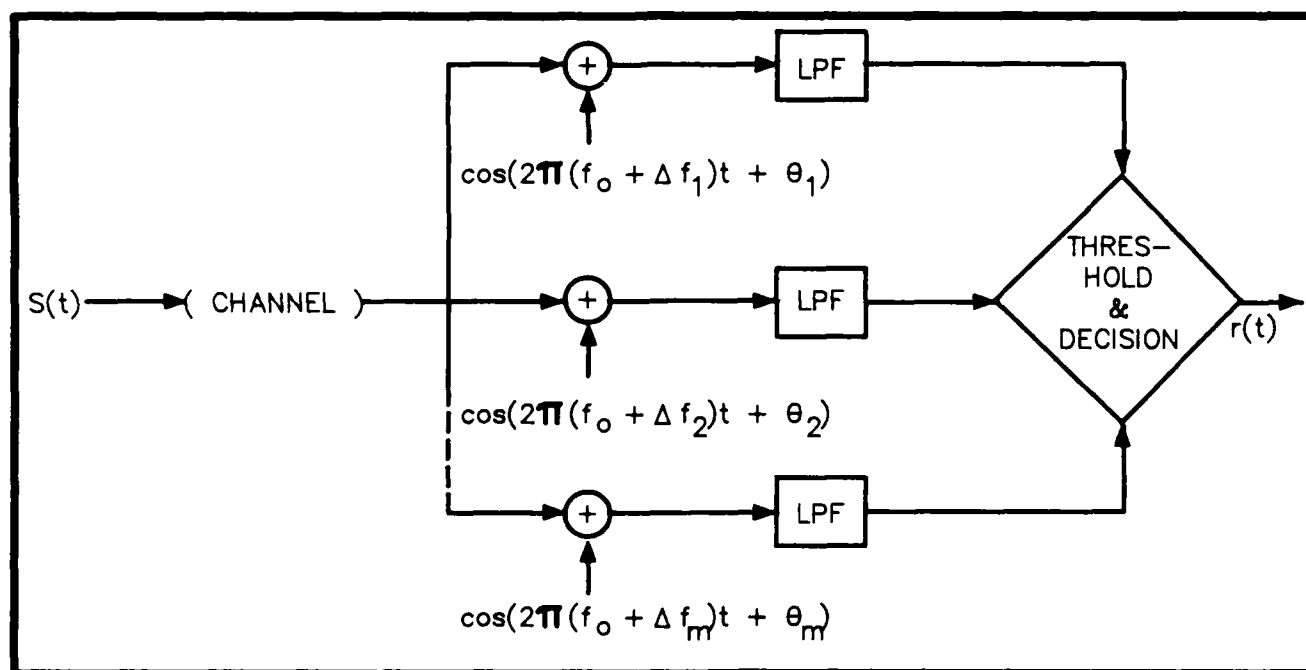


FIGURE 4.4-15a: M-ARY C-FSK

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$$f_c = f_o + f_m, \quad 1 \leq m \leq M,$$

where  $f_m$  represents the user-specified frequency deviation.

Therefore, the transmitted signal is represented by

$$S_m(t) = A \cos(2\pi f_c t + \theta_m).$$

A coherent FSK scheme is implemented by using  $M$  local oscillators at the receiver, as shown in Figure 4.4-15a.

A noncoherent FSK system (Figure 4.4-15b) is realized if a matched filter followed by an envelope detector is used at the receiver, instead of the oscillator/low pass filter combination of the coherent scheme.

**4.4.6.3 Unit 43 (Differential Phase Shift Keying).** Differential phase shift keying (DPSK) employs preprocessing prior to PSK modulation of the carrier so that local oscillators are not required at the receiver. Preprocessing consists of multiplying past and present symbols to compute a differentially encoded symbol for transmission. Therefore, DPSK modulated signals may be noncoherently demodulated. A DPSK system is illustrated in Figure 4.4-16.

#### **4.4.7 LLCSC8 (Channel Emulator)**

The channel emulator component is activated by the fast fade control distributor when modulation of the information signal has been performed at the Modulation/Demodulation component LLCSC7. The channel emulator component will simulate the fading nature of the channel, as well as the additive noise. Figure 4.4-17 illustrates this channel emulator.

**4.4.7.1 CSC5 (Fade Simulator).** There are two approaches to simulating the single-layer fading channel conditions, and in conjunction with the coefficient generator of UNIT47, the channel transfer function. The first fading channel simulation method is the  $f^{-u}$  law spectral estimate, and the second is the scattering function. The former method needs only the high-level

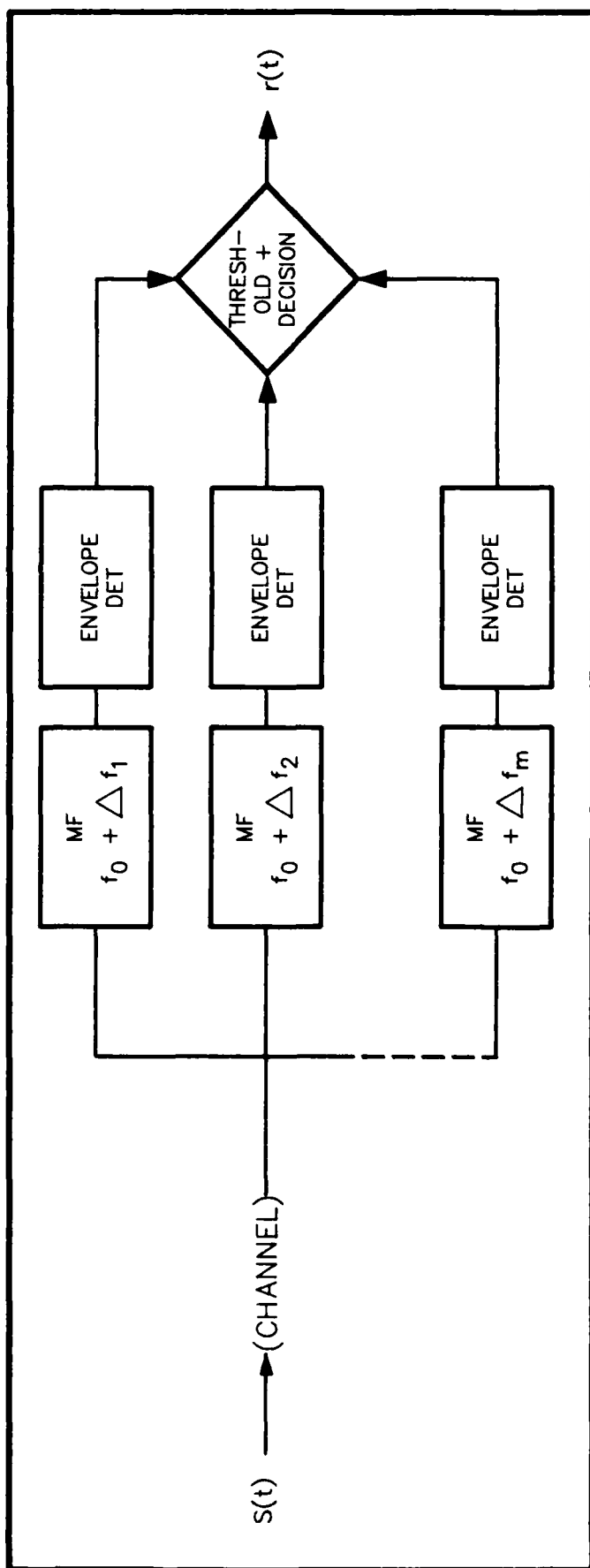


FIGURE 4.4-15b: M-ARY NC-FSK

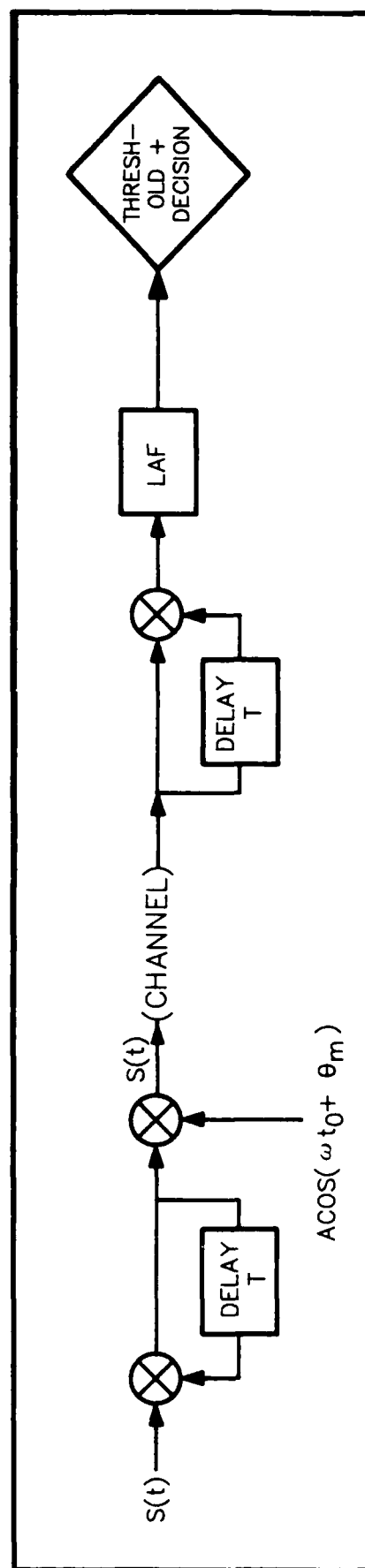
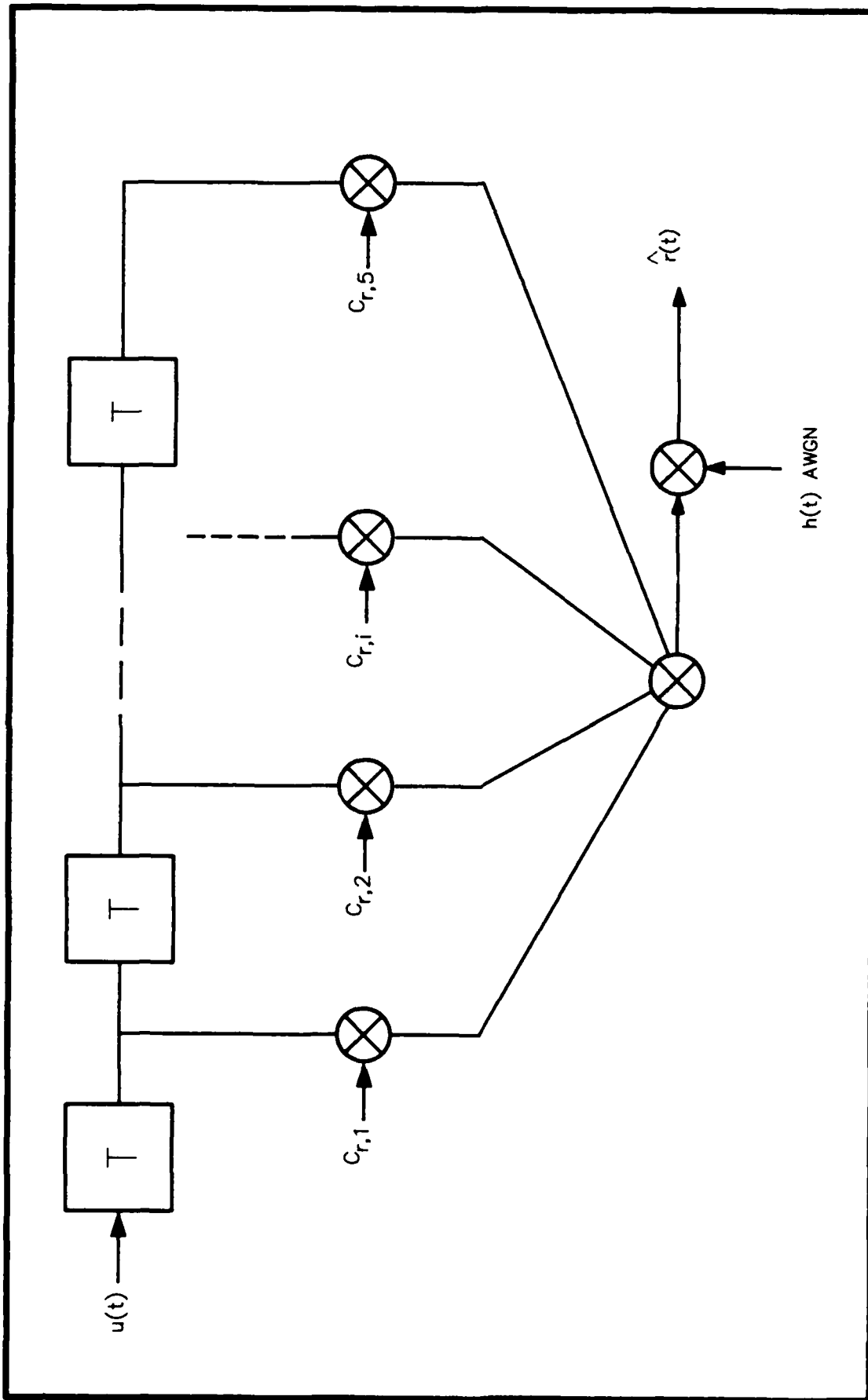


FIGURE 4.4-16: BINARY DPSK

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FIGURE 4.4-17: TAPPED DELAY LINE MODEL OF FADING CHANNEL

parameters, such as decorrelation time and coherence bandwidth in order to produce valid results. However, the latter method requires other, low-level parameters, including electron density, relative velocity, etc. Naturally, the latter method is more computationally complex, but yields a more realistic and more precise description of the channel, and subsequently, its transfer function.

The user also has the option to specify a multi-layered fading channel, with each layer exhibiting a different set of physical properties, in order to simulate a multiple nuclear burst environment. The channel emulator then would generate  $i$  ( $i$  corresponds to the number of layers) transfer functions, via either of the two above methods and the coefficient generator. The cascade realization of the individual transfer functions would represent the overall multiple layer transfer function. (In addition, for spatial diversity systems,  $L$  such statistically independent transfer functions are generated by the emulator.) If the user has specified no intermediate link signal processing for a double-link system (for example) a second channel transfer function is generated independently. The two are concatenated to effect the double link channel, through which the information signal will propagate. (For multi-layer models, an entire second set is generated.) The resulting BER using this channel transfer function will determine double-link performance. And, as discussed in TLCSC1, multi-time-segment, multi-link combinations can be evaluated also. (If onboard processing has been specified, two separate single-link performance evaluations (with appropriate parameter assignments and time-segment divisions) will yield the double-link results.)

All parameter values needed for calculating the spectral estimate or the scattering function are retrieved from the execution database. Similarly, all data generated in the two execution modules are stored in the execution database, as well as being transferred to the coefficient generator module by the fast fade control distributor. The coefficient generator uses these data values to produce the simulated channel transfer function.

4.4.7.1.1 Unit 44 (Spectral Estimate). This module is enabled by the fast fade control distributor under either of two conditions: the user has previously specified only the high-level parameters (decorrelation time, coherence bandwidth, etc.), or the user needs a fast estimate of the channel, not the rigorous "exact" computation provided by the scattering function method. Furthermore, because of the Doppler delay simplifications assumed, frequency selective channels will not be emulated via the spectral estimate method.

The spectral estimate of the channel is given by

$$S(f) = S_0 / (f^2 + f_0^2)^{u/2}, \quad u > 3,$$

where  $S_0$  is a normalization constant,  $f$  is the frequency shift,  $f_0$  is the outer scale of the spectral density, and  $u$  determines the spectrum roll-off.

With the power spectral density estimate, the channel variance (or rather a set of variances, since the channel is time-varying) may be computed by simple numerical integration over a sub-interval chosen so that the portion of the spectral density left unintegrated has negligible measure. (The overall interval of the spectral density is infinitely long; therefore, a finite sub-interval must be selected.) Following this operation, the tapped delay line coefficient generator of UNIT47 may be used to estimate the actual channel transfer function. (For multi-layer channel realizations, the number of sets of variances that would be generated corresponds to the number of layers in the multiple layer channel.)

4.4.7.1.2 Unit 45 (Scattering Function). The scattering function execution module was designed to determine an empirical formula of the channel scattering function. Since the scattering function is dependent on the low-level physical conditions, as well as high-level physical conditions like decorrelation time and coherence bandwidth, it will provide for a more realistic and accurate implementation of the channel transfer function than will the spectral estimate. However, because of the calculations necessary to determine the scattering function itself, the scattering function scheme is far more computationally complex and far slower than its spectral estimate counterpart.

The empirical formula of the channel scattering function is given by

$$S(K_p, \tau) = \left\{ \pi^{1/2} l_o^2 (f_c / \sigma_\phi^2)^{1/2} \exp(-K_p^2 l_o^2 / 4) \exp[-(K_p^2 l_o^2 / 4 (\Delta f)_c + 2\pi\tau)^2] \right. \\ \left. \cdot (f_c^2 / 2\sigma_\phi^2) \right\} (\gamma/B) \exp(\gamma^2 / 2B^2) K_{3/2}(\gamma^2 / 2B^2) \quad - s(f, \tau)$$

where  $f_c$  = carrier frequency,

$K_{3/2}$  = Bessel function of 3rd kind,

$l_o$  = decorrelation distance,

$\sigma_\phi^2$  = phase variance,

$(\Delta f)_c$  = coherence bandwidth,

$$\gamma^2 = l_o^2 (1 + f_c^2 / (\Delta f)_c^2 \sigma_\phi^2) (K_p^2 l_o^2 + 2\pi(\Delta f)_c \tau) / 8$$

$$B^2 = (l_o^2 / 4(\Delta f)_c)^2 (f_c^2 / 2\sigma_\phi^2)$$

$$K_p = 2\pi f / v$$

$v$  = relative velocity of scintillation medium with respect to receiver.

And since it is the two-dimensional Fourier transform of the channel autocorrelation function,  $R(\Delta w, \Delta t)$ :

$$S(f, \tau) \triangleq \iint R(\Delta w, \Delta t) e^{j\Delta w \tau} e^{-j\Delta t f} d(\Delta t) d(\Delta w),$$

$$R(\Delta w, \Delta t) \triangleq E\{c(w, jt) C^*(w_2; t + \Delta t)\},$$

$$\sigma_{cnm}^2 = R_{nm}(0, 0) = T \int_{\tau_m - \Delta\tau/2}^{\tau_m + \Delta\tau/2} \int_{(n-1/2)2\pi/T}^{(n+1/2)2\pi/T} S(K_p, \tau) d(K_p) d\tau \Big|_{\tau_m \rightarrow \pm\infty}$$

for flat  
fade

the variance(s) of the time-varying channel may be computed via double integration. The numerical integration will be performed in such a manner that the portion of the scattering function left unintegrated (if it has infinite support) has negligible measure. The variance(s) will be used subsequently in the coefficient generator module (UNIT47) for estimating the channel transfer function. (For multi-layer channel realizations, as in the spectral estimate method, the number of sets of variances corresponds to the number of layers in the multiple layer model.)

**4.4.7.1.3 Unit 46 (Coefficient Generator).** When activated by the fast fade control distributor, the coefficient generator uses the set(s) of variance values provided by either the spectral estimate module or the scattering function module to produce one (or more) sample transfer function(s) of the stochastic channel. More specifically, for each variance  $\sigma^2$ , the generator selects an in-phase component  $x_{nm}$  from the Normal distribution  $N(\mu, \sigma_K^2)$  and a quadrature component  $y_{nm}$  from  $N(0, \sigma_y^2)$ . For the in-phase component  $x_{nm}$ ,  $\mu$  will equal 0 for Rayleigh fading, and it will equal the signal (spectral) amplitude  $A$  for Rician fading. The fade type will have been determined by the system mode selector.

The two components are "summed" and transformed to produce the desired complex Rayleigh (Rician, etc.) coefficient  $C_{nm}$ . The component selection and summing process is repeated for each variance, ultimately resulting in the set of frequency sampled sequence coefficients  $\{C_{nm}\}_{NM}$ . The number of taps ( $M$ ) is equal to unity for frequency nonselective channels and is therefore not an important factor in calculations; otherwise, it is equal to the quotient of  $BW_s/(\Delta f)_c$ . Since  $N$  is a discrete frequency index, a discrete transfer function estimate of the channel is available, given by

$$C_i(z)|_{z=e^{j\omega}} = \{C_{1m} + C_{2m}z^{-1} + C_{3m}z^{-2} + \dots + C_{Nm}z^{-(N-1)}\}_i.$$

(The subscript denotes that this is the  $i$ -th layer transfer function of the multiple layer model. The overall transfer function would be represented by  $C(z) = \pi C_i(z)|_{z=e^{j\omega}}$ .) A flow diagram of the coefficient generation process is presented in Figure 4.4-18.

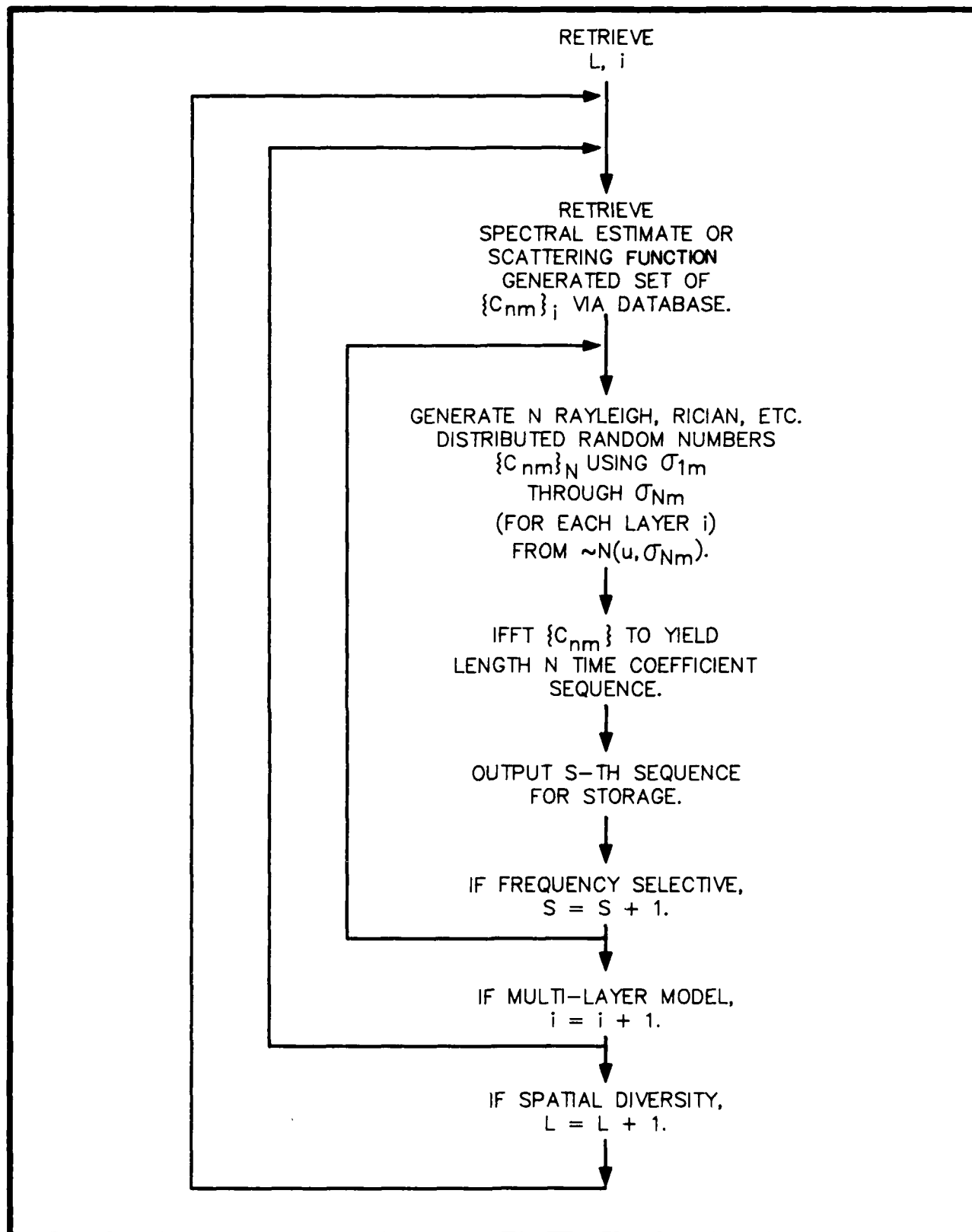


FIGURE 4.4-18: COEFFICIENT GENERATION

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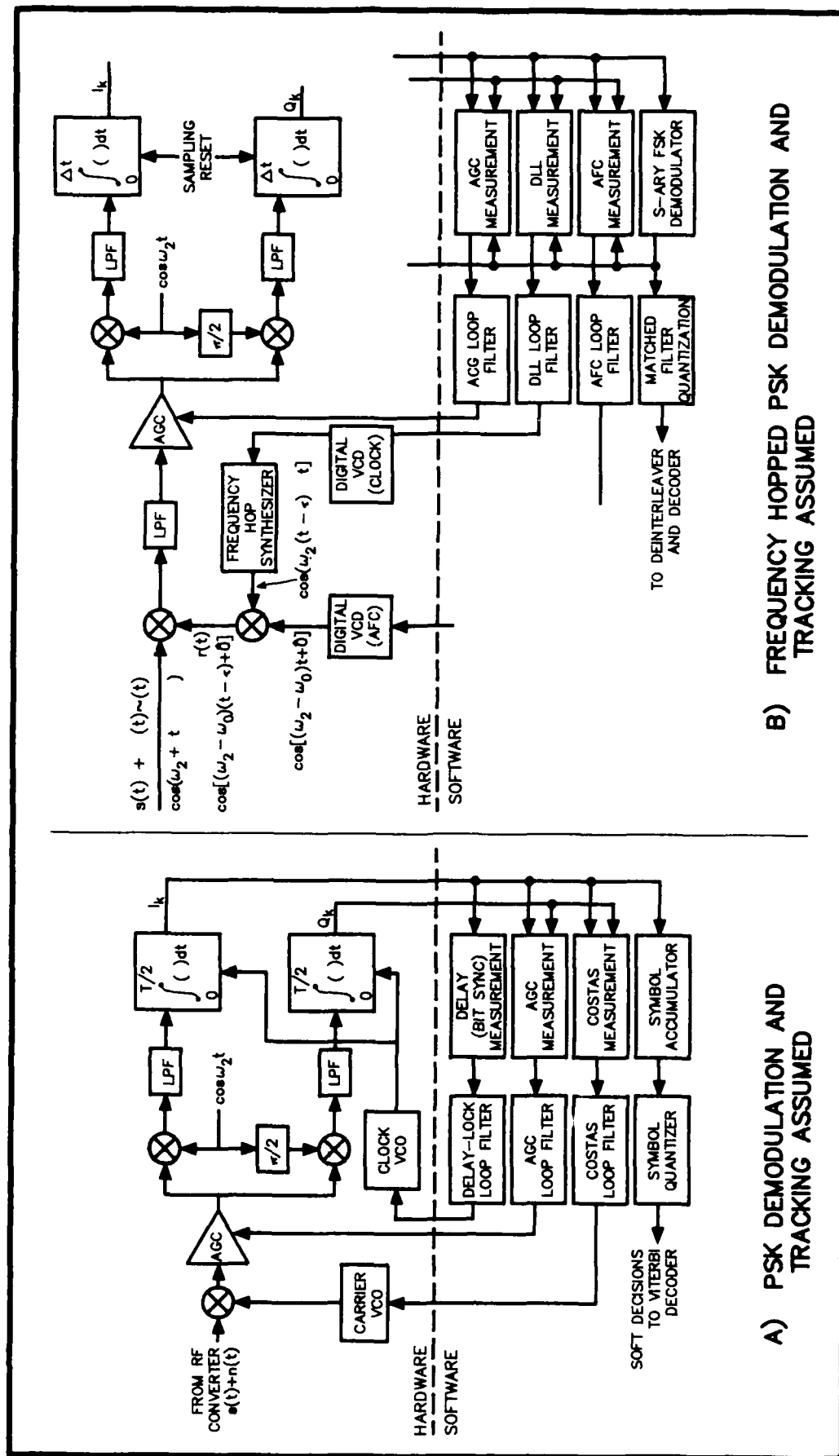
4.4.7.2 Unit 47 (AWGN). After the fading aspect of the channel has been simulated and the channel transfer functions have been established, the fast fade control distributor enables the noise generator module. The purpose of this module is to simulate the disruption of the modulated signal via additive white Gaussian noise. Therefore, the module again will draw from  $N(0, \sigma^2)$  to directly corrupt the information sequence. The additive noise is assumed to have a constant power spectral density spectrum of  $N_0/2$ . The resulting signal will be  $y_k = s_k + n_k$ , where  $s_k$  is the faded modulated signal and  $n_k$  is the additive noise. This set of noise parameters  $\{n_k\}$  will be stored in the execution database for subsequent access by the receiver/equalizer components.

#### 4.4.8 LLCSC9 (Preprocessor)

The preprocessor component readies the received signal (the frequency domain product of the signal and channel representations) for demodulation that will take place next in the Modulation/Demodulation component LLCSC7. These duties involve phase/frequency tracking, pre-filtering, frequency dehopping, and diversity combining.

4.4.8.1 Unit 48 (Tracking). Tracking is performed at the receiver, regardless of the modulation scheme the user has specified. This critical tracking module performs automatic gain adjustments for normalization of the incoming signal levels, and frequency tracking for proper synchronization of the receiver to the incoming signal. Furthermore, phase tracking is performed when the receiver uses a coherent demodulation scheme. Block diagrams of the tracking module appear in Figure 4.4-19 for a frequency hopped FSK system and also for a binary PSK system.

4.4.8.2 Unit 49 (Pre-Filtering). The pre-filtering process consists of shape filtering at the transmitter, followed by matched filtering (a process that matches the receiver filter to the spectrum of the transmitted signal) at the receiver. When the user specifies a frequency selective channel equalizer, pre-filtering is not necessary.



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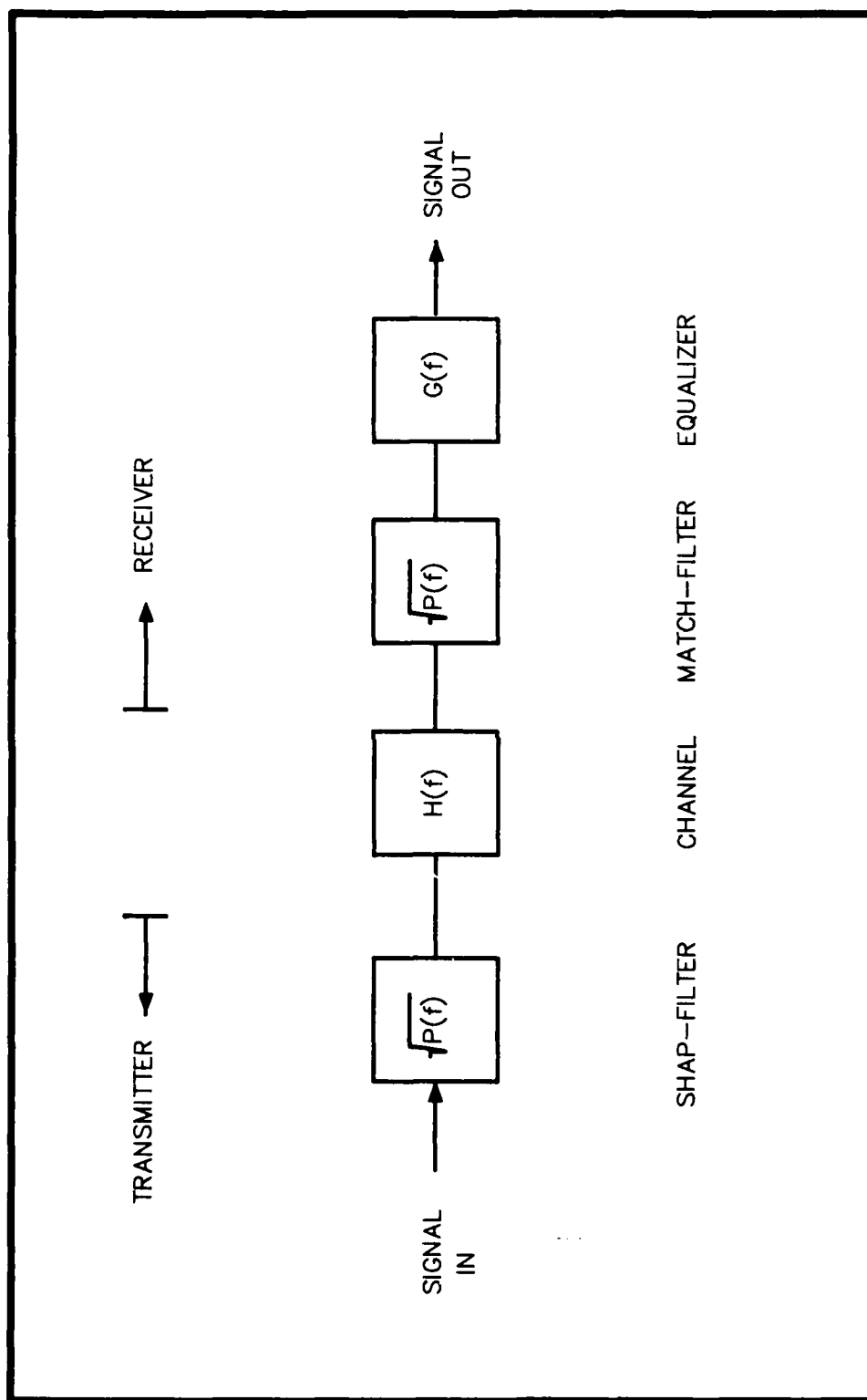
FIGURE 4.4-19: TRACKING MODULE BLOCK DIAGRAMS

The pre-filter  $P(z)$  is divided equally between the transmitter and the receiver, each having the transfer function  $\sqrt{P(z)}$ .  $\sqrt{P(z)}$ , then, is a Nyquist filter (such as the raised Cosine type) which shapes the transmitted pulse with the envelope  $\sqrt{P(z)}$ , and detects the transmitted pulse with its matched filter  $\sqrt{P(z)}$  at the front end of the receiver. The locations of the pre-filter(s) are shown in Figure 4.4-20.

The primary purpose of the pre-filter is to provide matched filtering for those instances when the signal level is greater than the user-specified acceptable fading level. When matched filtering of the signal is successful, significantly less computation will be required upon reaching the equalizer than when matched filtering is not successful.

**4.4.8.3 Unit 50 (Frequency Dehopping).** The frequency dehopping module is activated if the user has employed frequency hopped spread spectrum frequency diversity. The pseudorandom sequence, which corresponds to the hop access order of the transmitter modulation frequencies, is retrieved from the execution database. This sequence is then used to "tune" the receiver demodulator (actually, the receiver's matched filters), so that the receiver demodulator employs the identical set of frequencies in the same order as that used at the transmitter.

**4.4.8.4 Unit 51 (Summation Combining).** The summation combining module is enabled if the user has opted to implement spatial diversity. The signals  $v_i$  at each of the individual antennas are added together to form a new signal  $V = \sum v_i$ . The combined signal ( $V$ ) then will be passed through a symbol decision device. The symbol decision device operates in the same manner regardless of whether it receives a combined signal or an individual signal. Basically, the decision device assigns threshold category boundary values, based on calculations designed to minimize the probability of decision error. The boundary values may differ between the individual signal case and the combined signal case, depending on whether the levels of the incoming signal are symmetric with respect to the zero level. As each piece of the incoming signal is detected, it is placed within the appropriate threshold category. Because each threshold category is associated with a presignal transmission



SHAP-FILTER      CHANNEL      MATCH-FILTER      EQUALIZER

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FIGURE 4.4-20: PRE-FILTER SCHEME

symbol, the activation of a threshold category results in the output of a pretransmission symbol. Therefore, when the entire incoming signal has been recognized by the symbol decision device, the entire pretransmission symbol sequence will have been computed.

#### 4.4.9 LLCSC10 (Receiver)

This execution component is activated by the fast fade control distributor after demodulation; the Modulation/Demodulation component LLCSC7 extracts the information sequence from the corrupted, transmitted signal. There are two primary components to the receiver: the equalization component, which equalizes the processed baseband signal using a tapped delay line, and the chip combiner unit, which despreads direct sequence spread spectrum signals.

When the receiver component has completed all of its assigned tasks, the fast fade control distributor again assumes active status. If coding or interleaving has been implemented, the fast fade control distributor will next enable the time diversity component LLCSC5; otherwise, the BER module will be activated next.

4.4.9.1 CSC6 (Equalizer). The output sequence from the decision device of the summation combiner (when spatial diversity is used), or the output of the demodulators (when spatial diversity is not used), will be the input to the equalizer. However, before the fast fade control distributor enables the equalizer component, it will query the user for the particular equalizer algorithm he wishes the tool to employ. There are several algorithms from which to choose, each of which is implemented via a tapped delay line. A tapped delay line receiver is advantageous since its accuracy is proportional to the number of taps used, and since its transfer function is altered readily to desired specifications by adjustment of the taps (each tap represents a coefficient of the transfer function).

The equalizer options proposed as part of this module are the reciprocal, zero-forcing, least mean square error, fractionally spaced, and frequency selective algorithms. All of the algorithms have tap spacing  $T = 1/BW_s$ .

except for the fractionally spaced equalization scheme, which employs tap spacing  $T' = T/2$ , in order to mitigate signal spectrum aliasing effects suffered by conventional adaptive equalizers, at the cost of increased hardware complexity. Additional study of equalization will be performed in the follow-on to select the specific algorithms to be implemented.

4.4.9.1.1 Unit 52 (Reciprocal). The reciprocal equalizer (RE) attempts to completely negate signal distortion caused by corruptive channel fading (represented by the transfer function  $C(f)$ ). This channel equalization is accomplished with the RE response function

$$G(f) = 1/C(f),$$

implemented over the signal bandwidth. The RE cannot be ideally implemented with a finite length tapped delay line, but arbitrary accuracy may be realized by using a suitably large number of taps for approximating  $1/C(f)$ . The RE equalized output sequence is then passed to the post-processor.

4.4.9.1.2 Unit 53 (Zero-Forcing) The zero-forcing equalizer (ZFE) minimizes the mean square noise based on the constraint of eliminating intersymbol interference (ISI). The equalizer response function of the ZFE is given by

$$G(f) = C^*(f)/r(f),$$

where  $r(f) = \sum P(f-k/T) |C(f-k/T)|^2$ . The ISI removed output sequence from the ZFE is passed to the post-processor.

4.4.9.1.3 Unit 54 (Least Mean Square Error). The least mean square error (LMSE) equalizer, as the name indicates, minimizes the mean square error of the received signal. The equalizer response function of the LMSE is given by

$$G(f) = C^*(f)/[r(f) + 1/(E_b/N_0)].$$

The LMSE equalized output is transferred to the post-processor.

4.4.9.1.4 Unit 55 (Selective). This equalization module is applied for the case of a frequency selective channel, with  $T = 1/BW_S$  tap spacings. The number of taps ( $S$ ) corresponds to the integer quotient

$$S = BW_S / (\Delta f)_C.$$

Furthermore, the taps are estimates of the channel transfer function. These taps, together with the reference signals stored in the execution database (see Unit 40) implement a bank of  $S$  matched filters that will perform the signal detection/equalization. Refer back to Figure 4.4-20 of Unit 40 for the tapped-delay line frequency selective receiver. The selectively equalized sequence is passed to the post-processor.

4.4.9.1.5 Unit 45 (Fractionally Spaced). The final method of equalization uses fractionally spaced taps placed  $T' = T/2$  apart. This fractionally spaced equalizer (FSE) acts on the signal spectrum before aliasing and therefore can offset severe amplitude distortion more effectively than conventional adaptive equalizers. Also, the FSE is able to synthesize the phase delay correction during equalizer adaptation and is therefore almost independent of the sample timing epoch. Hence, FSE is advantageous for use in channels with severe phase distortion.

The equalizer response function used by the FSE can correspond to any of the reciprocal, zero-forcing, or least mean square error equalizer response functions. However, FSE's cannot be used for frequency selective equalization, since the  $1/BW_S$  tap spacings are critical for signal reception. The output of the equalizer is decimated to restore the original sampling time  $T$ , offsetting the interpolating effects of the FSE. The decimated sequence is subsequently passed to the post-processor.

4.4.9.2 Unit 57 (Chip Combining). The chip combining unit is activated by the fast fade control distributor after signal equalization if direct sequence spread spectrum has been used at the transmitter. The purpose of the chip combining module is for despreading direct sequence spread spectrum signals. The pseudorandom sequence of chips, used to multiply each of the bits of the

time diversified information sequence, are retrieved from the execution database and multiplied by the received signal to create a new product sequence. The number of chips per information bit then is recalled from the execution database and is used to despread the product sequence.

When the chip combining process is completed, the time diversity component LLCSC4 will be activated next by the fast fade control distributor. If the information sequence has been encoded, the corresponding decoding necessary will be performed via the Encoding/Decoding component CSC3. If interleaving has been used on the information sequence, the corresponding deinterleaving at CSC2 also will be performed.

#### 4.4.10 Unit 58 (FFT)

The fast Fourier transform (FFT) module is called by the fast fade control distributor whenever time-frequency transformations need to be performed on sequences. These sequences may include the information signal, channel impulse response, and myriad filter responses.

The need for transformations arises when two sequences are both in the time domain and a convolutional integral is necessary. For example, if one sequence is the information sequence and the other is a filter impulse response, the convolution of the two will result in the filter output response. But, since convolutional integrals are complex and difficult, transformations of the two sequences to the frequency domain, followed by a simple multiplication, and then another transformation of the product sequence will result in the output time sequence. Of course, if additional processing is to be performed on the product sequence, the final transformation most likely would not be performed.

Also, a transformation of one of the sequences is necessary when two sequences are in different domains. The sequence to be transformed would be chosen such as to avoid numerous computationally complex convolution integrals.

The FFT module therefore was included to promote computational efficiency. It should be noted, however, that the sequence lengths ( $I_N$ ) need to be a power of 2 ( $I_N = 2^1$ ) in order for the FFT module to operate properly.

#### 4.4.11 Unit 59 (BER)

When activated by the fast fade control distributor after necessary decoding and deinterleaving via the time diversity component LLCSC5, the BER module compares the received (processed) data sequence with the original data sequence stored in the execution database. The bit error rate simply is calculated by dividing the number of discrepancies between the two sequences by the total number of bits in the information sequence. The bit error rate provides a sample performance measure of the bit error probability. Longer (test) information sequences will yield more statistically significant measures of the bit error probability. A significance measure such as standard deviation or confidence limit will also be computed. Control is transferred back to the fast fade control distributor after this computation, which in turn activates the executive control distributor.

## SECTION 5

## ISSUES REMAINING TO BE RESOLVED

As indicated in Section 2, a number of issues remain to be resolved. These issues are divided into three categories: scenarios, computational and technical issues (the latter involving model implementation) and are discussed in the paragraphs that follow.

## 5.1 SCENARIO DEPENDENT ISSUES TO BE RESOLVED

5.1.1 Additional Scenario Parameters

The scenario definition includes the burst size, location (both absolute and relative to transmitter/receiver pair) and time after burst. But there are other scenario related parameters to consider. Nuclear detonations may also produced dust clouds (low altitude bursts), electromagnetic pulses and the fireball itself. As presently designed, the MASCOT model concentrates on simulation of ionospheric scintillations such as those induced by high altitude nuclear bursts. Considerations such as those mentioned above, although excluded in the Phase I effort, are worth addressing in a follow-on effort. Whether such additional effects are eventually to be modeled is a decision to be made early in the follow-on. The decision is one that may heavily depend upon the predicted accuracy of the results obtained, i.e., how realistic the results of the simulator are perceived to be in terms of communications modeling.

5.1.2 Multiple Detonations

Many realistic scenarios of interest could involve multiple bursts. This might be the intentional lay-down structure or it could evolve from salvage fusing or attacking ballistic missiles. The initial model described in this report is single event only, however. Although the precise method by which multiple detonations will be modeled remains to be resolved, STI's tentative solution is to bound the problem by considering the affects of each blast

independently and superimposing them on the signals. There can be nonlinear superpositions of these effects, but to understand this requires analyses that would have to be carried out under a follow-on effort.

### 5.1.3 Nonlinear Transponder Effects

For the MASCOT simulator only ideal, linear transponders were considered. In most physical communications systems, however, this assumption does not hold. That is, satellite transponders display nonlinear characteristics. For example, satellite transponder sharing is common, and in the scenario of two users of unequal power, the user with the lower input (to transponder) power suffers roughly a 6 dB suppression at the output; the higher input power user experiences an enhancement. As part of the future work, this transponder power sharing problem will be generalized to the n-user scenario. The results can then be incorporated with the existing design for MASCOT.

## 5.2 COMPUTATIONAL ISSUES TO BE RESOLVED

### 5.2.1 Accuracy and Run Time

One of the most significant issues remaining to be resolved concerns run time vs. validity of the resultant data. It is expected that use of analytic evaluation models techniques will result in considerable computational time savings (compared to simulation) for fading conditions. Tradeoffs between the number of phase screens and the points to be evaluated on each screen are expected to result in optimally reduced run time for the simulated fast fade conditions.

Additional savings may be possible depending upon the choice of input parameters. For example, direct input of a decorrelation time eliminates the steps involved in calculation of this parameter from the physical scenario. Potentially even more significant is the possibility of inputting an electron fluctuation density, as it may be possible to simplify calculation of the channel transfer function. Direct input of parameters such as  $\tau_0$  and  $\sigma_n$  could be used to bypass user scenario input, but at the price of reducing user

friendliness by requiring that the user be more familiar with the physical effects of a high altitude nuclear detonation. Otherwise the shortcut could result in a reduction in the user's ability to relate the physical scenario to simulated results. These and other tradeoffs between run time, model validity and practicality remain to be performed in order to finalize the model features.

### 5.3 TECHNICAL ISSUES TO BE RESOLVED

#### 5.3.1 Remote vs. Direct Inputs

Key model parameters and functions may be input either directly or indirectly. By direct input it is meant that the user manually provides the necessary data, whereas indirect inputs are fed to the model remotely from either another simulator or a data base. At present it is envisioned that the user will have the option to input scenario parameters, as well as transmitter/receiver functions and parameters, directly. Remote inputs from a data base will provide default values should the user so choose. As already noted, the choice between direct vs. indirect input will be made on the basis of user convenience and model performance.

#### 5.3.2 Outputs

The user will be able to select any of the key parameters to plot as output variables, as well as define new variables and scale factors for this purpose. Additionally, a set of standard output curves (e.g.,  $E_b/N_0$  vs. BER and  $E_b/N_0$  vs.  $\tau_0/T$ ) will be available for selection. The specific predetermined outputs, the nature of the plots, and the manner in which they will be implemented remain to be determined.

#### 5.3.3 Delineation Between Fast and Slow Fading

The STI nuclear scintillation communications modeling tool is designed to take advantage of the fact that performance of many systems may be directly calculated under slow fading conditions. While this may provide significant time

savings over the simulation approach required to analyze fast fading, it poses the problem of delineating between fast and slow fading. The ratio  $\tau_0/T$  provides information concerning the "speed" of the fading environment. As stated previously, the larger the value of  $\tau_0/T$ , the slower, or more narrow-band, the fading process. But  $\tau_0/T$  alone is insufficient to determine the type of fading environment. Other factors that must be considered include the modulation technique, type of coding (if any), link multiplicity, receiver structure, and perhaps others yet to be determined. For example, appropriate measures of the fading conditions vary with modulation type. Generally, PSK is more effective at higher data rates while FSK is more effective at lower data rates. The factor  $B_L T$ , where  $B_L$  is the Costa loop bandwidth and  $T$  the symbol duration as determined from code rate and alphabet, was found to provide important information concerning the performance of PSK and DPSK modulations in an environment described by a given  $\tau_0/T$ . On the other hand, the factor  $\tau_0/\Delta f$ , where  $\Delta f$  is the FSK tone separation, was found to provide similar information concerning FSK performance (i.e., refer to Figures 5-1 and 5-2) [23]. Knowledge of both  $\tau_0/T$  and either  $B_L T$  or  $\tau_0/\Delta f$  will be necessary in order to help distinguish whether fading conditions maybe more appropriately described as fast or slow for a specific modulation technique and receiver structure.

To summarize, it will be necessary to determine an effective and general means of discerning between fast and slow fading if the potential reductions in run time are to be realized when computation is used in place of simulation.

An approach that appears useful is to consider a transition region between fast and slow fading that could be divided into segments within which an incremental adjustment is imposed to correct computations. This would allow maximum use to be made of computational rather than simulation techniques. Such a method would be useful if at least a portion of the transition region between "fast" and "slow" fading conditions occurred gradually enough. This appears to be the case based on study of plots of required  $E_b/N_0$  for a fixed BER vs. either  $\tau_0/T$  or  $(\Delta f)_c T$  from several sources. In these,  $E_b/N_0$  was observed to vary slowly over several orders of magnitude before a more abrupt transition occurred.

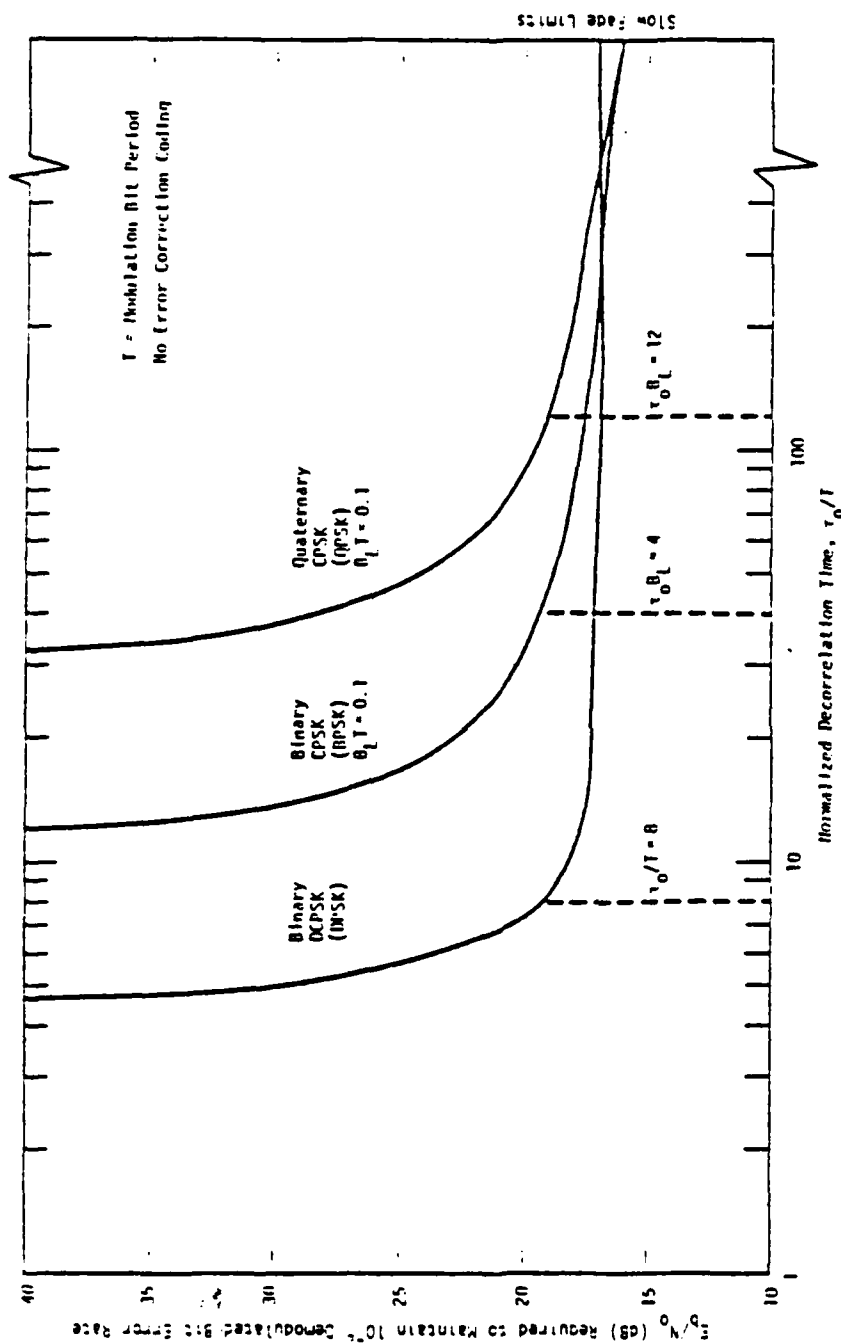


FIGURE 5-1: POWER REQUIRED TO MAINTAIN  $10^{-2}$  DEMODULATED BIT ERROR RATE AS A FUNCTION OF SIGNAL SCINTILLATION DECORRELATION TIME, PSK MODULATION.

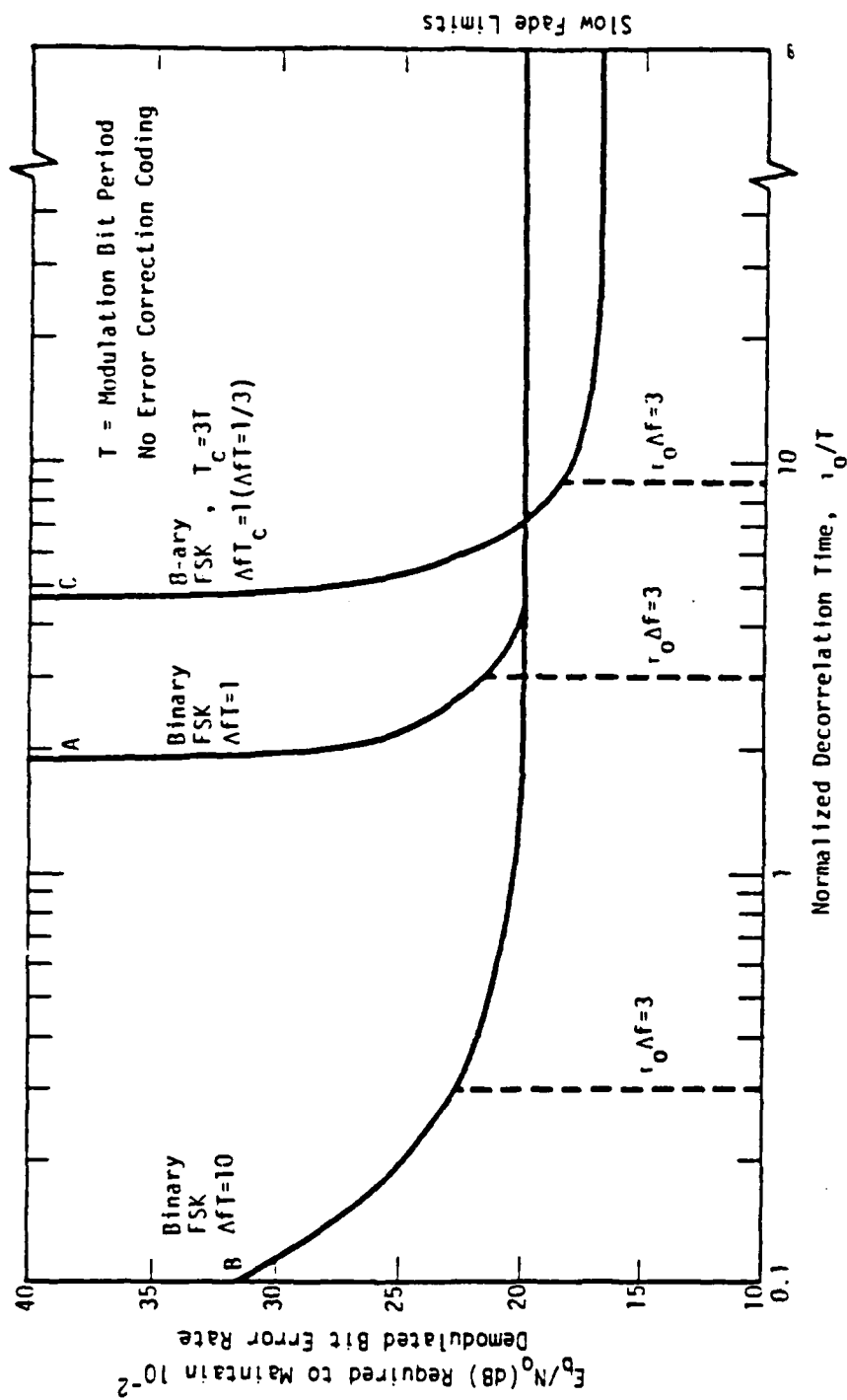


FIGURE 5-2: POWER REQUIRED TO MAINTAIN  $10^{-2}$  DEMODULATED BIT ERROR RATE AS A FUNCTION OF SIGNAL SCINTILLATION DECORRELATION TIME, FSK MODULATION.

#### 5.3.4 Adjustment for Imperfect Interleaving

High altitude nuclear detonations may produce scintillation effects with a wide range of decorrelation times. This poses particular difficulties for interleaving. When  $\tau_0/T$  is very small, interleaving is usually not required. On the other hand, large values of  $\tau_0/T$  may place practical constraints on the available interleaver span due to memory limitations. The result is a channel that may not be accurately modeled as memoryless even though an interleaver is utilized. It remains to be determined how an interleaving adjustment can be parametrically determined and applied to computations, especially in the region between what is clearly fast and slow fading.

#### 5.3.5 Implementation of Phase Screens

The last issue to be discussed concerns the implementation of phase screens in the fast fading model. The recommended number of phase screens and their composition was observed to vary from model to model. For example, the MPS model examined used ten phase screens while the PATS code model used only five. Although modulation techniques and other conditions varied, the basic output quantities (BER vs.  $E_b/N_0$ ) were found to be in good agreement. There was no noticeable degradation due to fewer phase screens with the PATS code model. As a result, the question arises as to how many phase screens should actually be implemented. The complexity of the screens must also be evaluated in terms of the number of points per screen at which the phase contribution will be evaluated. The optimum number of screens and points per screen to be considered remains to be determined, and it is intended that the resolution of this be based upon tradeoffs between run time and accuracy. Example criteria might include: (1) the number of phase screens and points to be implemented will be the minimum required to achieve the desired accuracy; or (2) the desired degree of accuracy is chosen such that no significant degradation may be observed between output curves of MASCOT and similar curves based on available empirical data or results of widely accepted models such as MPS or PATS.

### 5.3.6 Antenna Effects

One aspect of modeling that has been neglected in the design is the effect of beam wander on the antennas. Although STI collected the relevant briefings and reports [25-29], the topic was omitted due to lack of time. One effect of the nuclear environment is to induce wander into the apparent arrival angle of the beam. As a result the signal is subject to antenna gain variations. Because beam wander is a time-dependent phenomenon, it introduces a fading process of its own. This becomes important for narrow beam antennas where the wander can occasionally induce a deep null. If the angular wander standard deviation is small compared to the antenna beamwidth, the effect can be modeled as an average power loss of an amount that is computable from the angular variance, the beamwidth and the line of sight. For very large wanders, actual beam patterns would have to be used.

A secondary effect is that the beam wander is correlated with delay spread. Energy arriving at large angles is also delayed more than the direct path signal, and hence a frequency selectivity is imposed, the bandwidth of which is calculable from the same parameters. The current MASCOT model only incorporates the direct and delayed signals as though arriving from a single direction. The beam wander extension will be included in the follow-on effort.

## SECTION 6

## RECOMMENDATIONS

The simulator is a flexible tool, capable of assessing many communications systems and environments. Continuation into a follow-on contract would satisfy the ultimate goal of realizing and implementing the simulator.

The resulting model description is viewed as a preliminary design. In the process of building the simulator, it will change many times. What has been accomplished that is important is that the process of coming to a preliminary design has been worked out by a complete pass through the design. Further iterations to be accomplished in a follow-on effort will fit the pattern of this development.

## 6.1 DELINEATION BETWEEN FAST AND SLOW FADING

It will be necessary to determine an effective and general means of discerning between fast and slow fading if the potential reductions in run time are to be realized when computation is used in place of simulation.

An approach that appears useful is to consider a transition region between fast and slow fading that could be divided into segments within which an incremental adjustment is imposed to correct computations. This would allow maximum use to be made of computational rather than simulation techniques. Such a method would be useful if at least a portion of the transition region between "fast" and "slow" fading conditions occurred gradually enough. This appears to be the case based on study of plots of required  $E_b/N_0$  for a fixed BER vs. either  $\tau_0/T$  or  $(\Delta f)_C T$  from several sources. In these,  $E_b/N_0$  was observed to vary slowly over several orders of magnitude before a more abrupt transition occurred.

## 6.2 ADJUSTMENT OF IMPERFECT INTERLEAVING

High altitude nuclear detonations may produce scintillation effects with a wide range of decorrelation times. This poses particular difficulties for interleaving. When  $\tau_0/T$  is very small, interleaving is usually not required. On the other hand, large values of  $\tau_0/T$  may place practical constraints on the available interleaver span due to memory limitations. The result is a channel that may not be accurately modeled as memoryless even though an interleaver is utilized. It remains to be determined how an interleaving adjustment can be parametrically determined and applied to computations, especially in the region between what is clearly fast and slow fading.

## 6.3 IMPLEMENTATION OF PHASE SCREENS

The question arises as to how many phase screens should actually be implemented. The complexity of the screens must also be evaluated in terms of the number of points per screen at which the phase contribution will be evaluated. The optimum number of screens and points per screen to be considered remains to be determined, and it is intended that the resolution of this be based upon tradeoffs between run time and accuracy. Example criteria might include: (1) the number of phase screens and points to be implemented will be the minimum required to achieve the desired accuracy; or (2) the desired degree of accuracy is chosen such that no significant degradation may be observed between output curves of MASCOT and similar curves based on available empirical data or results of widely accepted models such as MPS or PATS.

## 6.4 ANTENNA EFFECTS

One aspect of modeling that has been neglected in the design is the effect of beam wander on the antennas. Although STI collected the relevant briefings and reports [25-29], the topic was omitted due to lack of time. One effect of the nuclear environment is to induce wander into the apparent arrival angle of the beam. As a result the signal is subject to antenna gain variations. Because beam wander is a time-dependent phenomenon, it introduces a fading process of its own. This becomes important for narrow beam antennas where the

wander can occasionally induce a deep null. If the angular wander standard deviation is small compared to the antenna beamwidth, the effect can be modeled as an average power loss of an amount that is computable from the angular variance, the beamwidth and the line of sight. For very large wanders, actual beam patterns would have to be used.

A secondary effect is that the beam wander is correlated with delay spread. Energy arriving at large angles is also delayed more than the direct path signal, and hence a frequency selectivity is imposed, the bandwidth of which is calculable from the same parameters. The current MASCOT model only incorporates the direct and delayed signals as though arriving from a single direction. The beam wander extension will be included in the follow-on effort.

## APPENDIX A

## NOTATIONS USED

Link-Budget Parameters

Antenna Gain: (Receiver, Transmitter)	$G_{AR}, G_{AT}$
Effective Isotropic Radiated Power	$P_{EIRP}$
Free Space Loss	$L_{FS}$
System Noise Temperature	$T_{sys}$

Modulation Performance

Binary (PSK)	B(PSK)
Coherent (PSK)	C-PSK
Differential Phase Shift Keying	DPSK
Frequency Shift Keying	FSK
M-ary (PSK)	MPSK
Non-Coherent (FSK)	NC-FSK
Phase Shift Keying	PSK

Performance Parameters

Bit Error Rate	BER
Probability of Bit/Symbol Error	$P_E, P_B, P_C$
Signal-to-Noise Ratio	$E_b/N_0$

Probability Density Functions

Gaussian

$$[1/(1/2\pi)^{1/2} \sigma] \exp(-A^2/2\sigma^2)$$

Rayleigh

$$[2A/E(A^2)] \exp(-A/E(A^2))$$

Double-Link

$$2K_0 [2A/4\sigma^4] / (4\sigma^4)$$

Rician

$$\frac{A}{2\pi\sigma^2} e^{-(A^2+S^2)/2\sigma^2} I_0 \frac{AS}{\sigma^2}$$

Channel Parameters

Available Bandwidth

W

Average Fade Duration

 $T_a$ 

Channel Transfer Function

 $C(f), C(z)$ 

Coherence Bandwidth

 $(\Delta f)_c$ 

Decorrelation Time

 $\tau_0$ 

Doppler Spread

 $B_d$ 

Electron Density

e

Layer Number of Multi-Layer Model

i

Phase Error Variance

 $\sigma_\phi^2$ 

RMS Phase Deviation

 $\sigma_{RMS}$ 

Relative Velocity

V

Unavailability Time

U

Diversity Parameters

Code Rate

 $R_C$ 

Error Correction Capability

E

Frequency Diversity

N

Interleave Length	$I_L$
Spatial Diversity	$L$
Viterbi Algorithm Constraint Length	$K$
Coding Parameters (Total number bits, Information bits)	$(n,k), (N,K)$

Receiver Parameters

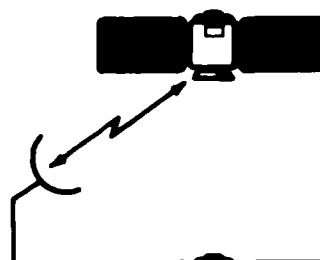
Equalizer Transfer Function	$G(f), G(z)$
Tracking Loop Bandwidth	$B_L$
Number of Taps	$m$
Pre-Filter Transfer Function	$P(f), P(z)$
Tap Spacings	$T$

Signal Parameters

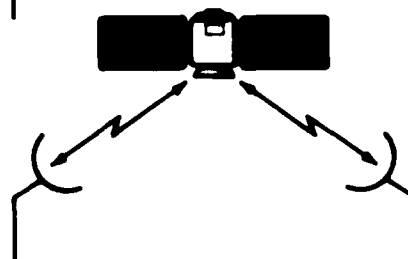
Alphabet Size	$M$
Bit/Data Rate	$R_D$
Carrier Frequency	$f_c$
Information Sequence Length	$I_N$
Pulse Duration	$T_s$
Signal Amplitude	$A, V$
Signal Bandwidth	$BW_s$
Signal Power	$S$
Tone Separation	$f_\Delta$
Variance (Based on Gaussian)	$\sigma^2$

# System Configuration

Single Link



Double Link  
Single Hop



## Other Constants and Notations

Boltzmann's Constant

$k$

Condition Probability of  $x$  given  $y$

$P(x|y)$

Discrete Time Index

$n$  or  $k$

Expected Value of  $()$

$E()$

Frequency Index

$m$

Probability Density Function of  $()$

$p()$

Speed of Light

$c$

## APPENDIX B

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